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NEUTRON AND FISSION FRAGMENT DAMAGE IN ZIRCONIA

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Wittels and Sherrill[1] reported recently that the irradiation-induced phase transformation observed in natural zirconia[2] does not take place when synthetic ZrO_2 crystals or powders are exposed to neutrons. Their analysis indicates that considerable quantities of uranium are present in the natural material and it is suggested that the phase transformation is due to fission spikes.

Our work[3] confirms the conclusion that pure ZrO_2 does not undergo phase transformation under neutron bombardment but we did observe a monoclinic to cubic phase change in oxidized zirconium alloys, containing up to 5 weight percent of either vanadium, chromium, or tantalum under moderate neutron doses. Materials used in the preparation of these alloys were of commercially pure quality and later analysis did not reveal uranium contamination. This suggests that the phase transformation in ZrO_2 takes place only in materials containing impurities which may provide nuclei of a cubic or tetragonal phase. Uranium is known to stabilize tetragonal ZrO_2,[4] and, although fission fragments undoubtedly accelerate the transformation rate, without the stabilizing effect of the uranium impurity they would not produce the transformation. The evidence for this comes from our experiments in which we irradiated spectroscopically pure ZrO_2 with fission fragments from an outside source.

It was reported at the Second Geneva Conference[5] that phase transformation can be produced in thick oxide layers formed on zirconium alloys by bombarding them with fission products from a uranium oxide film placed opposite the ZrO_2 layers at a distance of about 1-2 mm. These experiments were subsequently repeated with oxides on sponge zirconium and on spectroscopically pure ZrO_2. The transformation was observed in all cases but it was also found that ZrO_2 was heavily contaminated with uranium which "evaporated" from the film. This "evaporation" of uranium is associated with the escape of fission fragments[6] and, although it cannot be avoided, uranium may be prevented from reaching the surface of ZrO_2 if a very thin aliuminum foil is placed between the fission fragment source and the specimen. The absorption of fission fragment energy in the aluminum foil is small when the latter is less than 1 micron thick.

Experiments with aluminum foils 0.7 micron thick showed that pure monoclinic ZrO_2 did not transform into cubic at doses which, in the absence of the aluminum foil, would have produced 100% transformation. A further experiment was performed in which the gap between the source and target was reduced from 2 mm to zero. By this means any effect due to the absorption of fission fragment energy in the aluminum foil was offset by elimination of the absorption in the air gap. A very small percentage transformation was found following this experiment, but this was ascribed to failure of the aluminum foil since a small α count indicating the presence of uranium was obtained from the target.

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[1] M. C. Wittels and F. A. Sherrill, J. Appl. Phys. 27, 643 (1956).

[2] M. C. Wittels and F. A. Sherrill, Phys. Rev. Letters 3, 176 (1959).
[3] J. Adam and B. Cox, J. Nuclear Energy A11, 31 (1959) and Atomic Energy Research Establishment, Harwell Report M415, April, 1959 (unpublished).
[4] G. N. Wolten, J. Am. Chem. Soc. 80, 1772 (1958).
[5] Dawson, Cox, Murdoch, and Sowden, Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958 (United Nations, Geneva, 1958), Paper P/46.
[6] B. V. Ershler and F. S. Lapteva, J. Nuclear Energy 4, 471 (1957).

SELF-ABSORPTION AND TRAPPING OF SHARP-LINE RESONANCE RADIATION IN RUBY

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As an aid in planning a microwave-optical double resonance experiment,[1,2] we have examined by high-resolution optical spectroscopy the details of the sharp-line fluorescence of ruby (Cr^{3+} in Al_2O_3).

The only transition which appears in the fluorescence of dilute ruby at 4°K is from $^2E(\bar{E})$ to $^4A_2$ and appears at 6934 A. Selection rules for this transition have been calculated,[3] and partially verified for absorption.[4] The Zeeman levels to be discussed here are those occurring for a magnetic field parallel to the symmetry axis and are shown in Fig. 1.

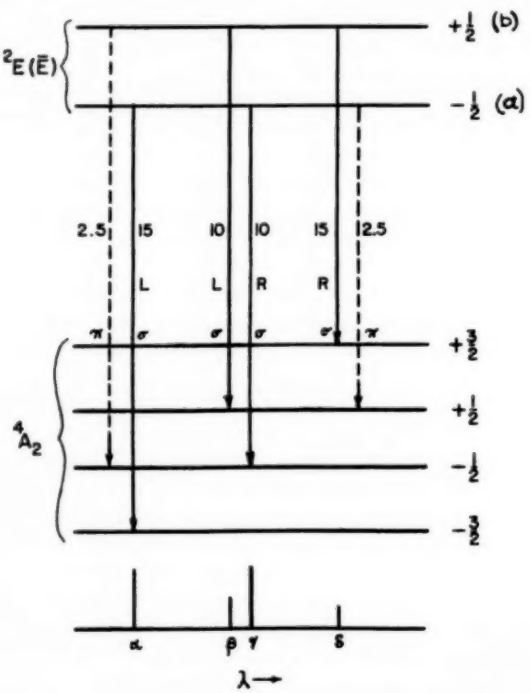

FIG. 1. Energy levels and transition probabilities for Zeeman levels involved in the resonance lines of ruby. $H \| c$ axis.

Figure 2(a) gives the predicted and observed intensities for a dilute ruby containing about 10^{-6} Cr per Al, and showing no color. For the theoretical patterns complete thermalization among the Zeeman levels is assumed in both ground and excited states. The figure shows that the selection rules predicting a 3:2 ratio of components α to γ and of δ to β are confirmed. Moreover, use of the α to δ and γ to β ratios shows that the population of atoms in the upper Zeeman level of the excited state is only slightly above that of a Boltzmann distribution. The effective spin temperature is 1.77°K. If it is assumed (although this is doubtful) that the excita-

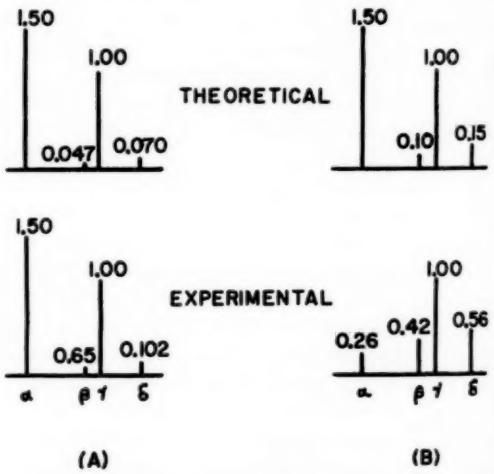

FIG. 2. (a) Theoretical and observed intensity ratio of Zeeman components in very dilute ruby sample (white sapphire). $H = 30\,000$ gauss; $T = 1.58$°K. (b) Theoretical and observed intensity ratio of Zeeman components in ruby containing 0.05% Cr_2O_3. $H = 30\,000$ gauss; $T = 2.1$°K.

tion process populates the two levels equally, and that the actual population is obtained by a balance between spin-lattice relaxation and radiative decay, the spin-lattice relaxation time is about 2×10^{-4} second. Also the crystal may have been heated above the helium bath temperature by the exciting radiation, so the actual relaxation time may be somewhat less. In any case, it seems that there is nearly complete thermalization between the Zeeman levels of the excited state during its relatively long lifetime of several milliseconds.

The great disparity between calculated and observed intensities for a ruby containing 0.05% Cr_2O_3 by weight is shown in Fig. 2(b). This disparity is explained by self-absorption which differs from one component to the next because of the Boltzmann population distribution of the ground-state levels. Thus component α terminates on the ground level ($m=-3/2$), which is populated by 85% of the atoms and is strongly absorbed. At the other extreme the component δ terminates on the $+3/2$ level, which is 8.3 cm^{-1} above it, and contains only 0.3% of the atoms, so that δ is much less absorbed. While self-absorption is often encountered in gaseous luminescence, it is seldom possible for a gas to be cold enough to have appreciably different populations in individual Zeeman levels.

Quantitatively, we find that an absorption coefficient of about 25 cm^{-1} for the α component produces satisfactory agreement with the observed intensity ratio of γ to α in the 0.05% ruby spectrum. A direct absorption measurement at 77°K, where only half of the atoms are in the $\pm3/2$ state and line widths have increased from 0.25 to 0.32 cm^{-1}, gave $k=13$ cm^{-1} in good agreement. The radiative lifetime of the excited state was also measured in the very dilute sample, and in finely divided and dispersed 0.05% ruby, and was found to be 4.3 ± 0.3 milliseconds. This gives an oscillator strength $f=7.5\times10^{-7}$ for the same transition, which then gives $k=11$ cm^{-1} for 0.05% ruby. This satisfactory agreement indicates that the observed lifetime is indeed predominantly radiative.

It has been possible in the 0.05% ruby to observe for the first time in a solid the trapping of resonance radiation. At 77°K the radiative lifetime is found to vary smoothly from 4.3×10^{-3} second for a fine, dispersed powder to 15×10^{-3} second for a whole boule, a very long lifetime. The observation of trapping confirms the predominantly radiative character of the decay of the excited state, and the strong self-absorption of the resonance radiation. The ratio of lifetimes with and without trapping is only about 4, showing that other modes of decay such as radiation in vibrational sidebands and nonradiative processes also occur.

We are indebted to D. G. Thomas for the use of his spectrograph and magnet, to A. M. Clogston, S. Geschwind, and S. Sugano for helpful discussions, and to G. E. Devlin for extensive experimental assistance.

[1]Geschwind, Collins, and Schawlow, following Letter [Phys. Rev. Letters 3, 545 (1959)].

[2]Brossel, Geschwind, and Schawlow, this issue [Phys. Rev. Letters 3, 548 (1959)].

[3]S. Sugano and Y. Tanabe, J. Phys. Soc. (Japan) 13, 880 (1958).

[4]S. Sugano and I. Tsujikawa, J. Phys. Soc. (Japan) 13, 889 (1958).

OPTICAL DETECTION OF PARAMAGNETIC RESONANCE IN AN EXCITED STATE OF Cr^{3+} IN Al_2O_3

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(Received November 12, 1959)

We have observed paramagnetic resonance in an excited metastable state of Cr^{3+} in Al_2O_3 by a method of optical detection which should have wide applicability to the general problem of studying paramagnetic resonance in excited states of ions in solids. This method makes use of the selective reabsorption in the ground-state Zeeman levels of the fluorescent light from the excited states in solids at very low temperatures.[1] Referring to Fig. 1 of the preceding Letter,[1] at 1.6°K, the lower of the two Zeeman levels of the excited state $\bar{E}(^2E)$ will be much more heavily populated. Let us first assume there is no reabsorption so that the theoretical

intensities for transitions to the Zeeman levels of the $^4A_2$ ground state are as given by Sugano and Tanabe.[2] In this case, when the sample is irradiated with microwave energy of the proper frequency so as to excite ions in the lower Zeeman level of $\bar{E}(^2E)$ to the upper Zeeman level, the ions upon radiating to the ground state emit two σ lines, δ,β of relative intensity 3:2 just as they do in radiating from the lower Zeeman level of the excited state (α,γ). In this case, the total emitted light in σ polarization would remain constant, i.e., it is independent of the relative population of the magnetic sublevels of the excited state. Similarly for the π component. On the other hand, if there is reabsorption of the fluorescent light, components β and δ originating from level b will be less strongly absorbed than α and γ due to the larger Boltzmann populations of the lower Zeeman levels in the ground state at low temperatures. Then, by inducing microwave transitions between the magnetic sublevels of the excited state so as to raise ions from level a to b, we can increase the total light output and thereby detect paramagnetic resonance in the upper state.[3] In contrast to standard optical double resonance techniques in gases, where normally a change in linear or circular polarization is detected along the field direction,[4] this method of utilizing selective reabsorption enables one to observe a change in the light in linear polarization in the much more convenient direction at right angles to the field.

The sample was a $\frac{1}{8}$-in. diameter by $\frac{1}{4}$-in. long cylinder of ruby, containing 0.05% of Cr, whose c axis was perpendicular to the axis of the cylinder. It was placed along the axis of a cylindrical $TE_{0,1,2}$ mode K-band cavity with a hole cut in one end wall for continuous vertical illumination from below by a 200-watt Osram mercury lamp. The ions were continuously excited to the metastable state by absorption of the 5461A and the 4000A light from the mercury lamp and subsequent decay by radiationless transitions to the metastable state. The metastable state $2\bar{A}(^2E)$, 30 cm^{-1} above, is virtually depopulated at 1.6°K, i.e., the thermalization of the metastable states in the radiationless decay is much faster than the radiative lifetime of these states. Slots were cut in the side wall of the cavity to view the fluorescent light which was detected by a photomultiplier preceded by a polaroid, collimating lens, and narrow band interference filter of 70A half-width centered at 6934 A. The microwaves were chopped with a 30-cps square wave and the resulting 30-cps component in the fluorescent light, as one swept the dc magnetic field through the excited state resonance, was recorded using standard lock-in detection techniques. A recorder trace of the increase in σ light is shown in Fig. 1. The line width is 17 gauss and is comparable to the widths observed in the ground-state resonances. We estimate that this signal arises from approximately 10^{10} Cr^{3+} ions in the excited state.

The excited state can be represented by an effective spin Hamiltonian

$$\mathcal{H} = \mu_\beta \vec{H}\cdot\tilde{g}\cdot\vec{S}', \qquad (1)$$

where $\vec{S}'$ is an effective spin of $\frac{1}{2}$. The energy levels of the excited state are given by $W=\pm\frac{1}{2}g\mu_\beta H$, where $g=(g_\parallel{}^2\cos^2\theta+g_\perp{}^2\sin^2\theta)^{1/2}$. The variation of the dc magnetic field required for resonance, H_{res}, as a function of the angle θ between the c axis and H_{res}, is shown in Fig. 2. $1/H_{res}$ is seen to vary as $\cos\theta$ within the accuracy of our measurements,[5] with the components of the g tensor given by $g_\parallel = (-)2.445\pm0.001$ and $|g_\perp|<0.06$. While the sign of $g_\parallel$ has not actually been measured by using microwaves of circular polarization, theoretical analysis by Clogston[6] indicates that it is negative.

The actual increase in the total fluorescent signal when the Zeeman levels of the excited state were saturated amounted to 2.5% of the total fluorescence. This very large light signal made it possible to measure directly the relaxation time T_1 in the excited state. Figure 3(a) is an oscillogram of a sample of the microwave power, square-wave modulated at 50 cps, incident on the cavity. Figure 3(b) is an oscillogram of the

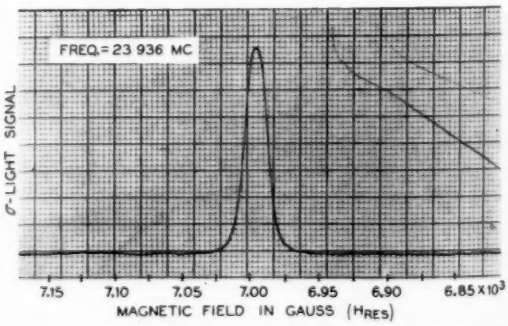

FIG. 1. Recorder trace of increase in σ component of fluorescent light as magnetic field is swept through resonance of excited $\bar{E}(^2E)$ state. This signal corresponds to approximately 10^{10} Cr^{3+} ions in the excited state. H is parallel to the c axis.

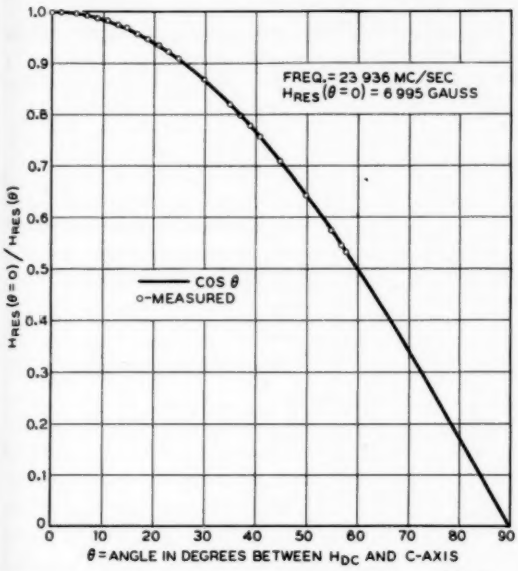

FIG. 2. Variation of magnetic resonance of $\bar{E}(^2E)$ state with angle θ between the applied field and the c axis of the crystal.

corresponding light signal. From the decay of the light signal with microwave power off, we determine T_1 to be 2.3 milliseconds. T_1 need not necessarily be a spin-lattice relaxation time; it is, however, the time taken for the magnetic sublevels of the excited state to thermalize when saturated, irrespective of the process, i.e., direct spin-lattice, cross-relaxation to ground-state spins, or even radiative relaxation. It is this latter radiative lifetime τ which sets an upper limit on the nonradiative T_1 which can be observed. Since τ is known to be about 8×10^{-3} sec, the value of T_1 of 2.3×10^{-3} sec can be assumed to be mainly connected with nonradiative thermalization. Further evidence for this is the speedup in T_1 to $\sim1.6\times10^{-3}$ sec at certain angles θ where the energy separation of the excited state approaches the Zeeman separation of some of the ground-state levels.

From a study of the saturation of the light signal with microwave power, the value of microwave power where $(\vec{\mu}\cdot\vec{H}_{rf}/\hbar)^2 T_1 T_2 \sim 1$ was determined. Since we know T_1 and T_2 (the latter from the line width) we could determine $\vec{\mu}$, the magnetic dipole moment matrix element for the transition, if we knew $\vec{H}_{rf}$ as a function of the microwave power level incident on the cavity. As it is difficult to know the exact field configu-

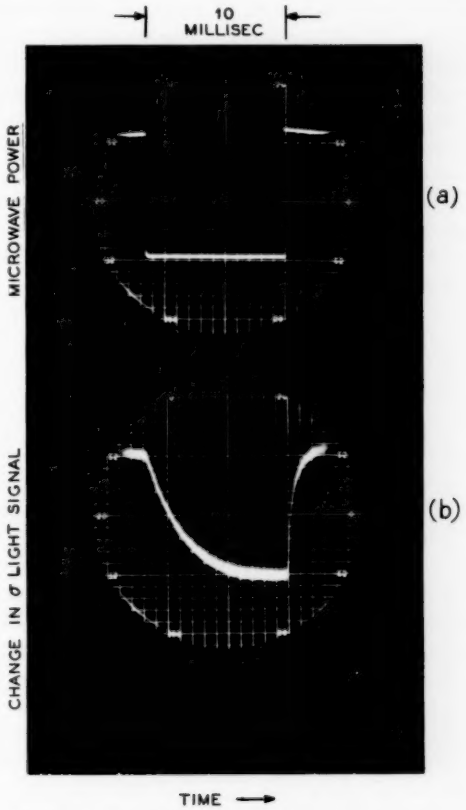

FIG. 3. (a) Oscillogram of microwave power square-wave modulated at 30 cps. The lower portion of the square-wave corresponds to the microwave-power-off part of the cycle. (b) Corresponding change in the σ component of the fluorescent light signal. From the decay of the increased fluorescent light signal when the microwave power is turned off, T_1 for the excited state ions is found to be 2.3 milliseconds.

ration in the ruby, we made a rough estimate of $\vec{\mu}$ by comparing the ratio of powers needed to saturate the excited state compared to the ground state, using the values of T_1 and T_2 for the ground state from other work. We find the ratio of the transition probabilities to be approximately 0.005. Even this small transition probability is relatively large compared to that originally predicted theoretically.

We have also detected the ground-state resonances, by monitoring the change in fluorescent light when these resonances are swept through, again due to selective reabsorption. However, these are of secondary interest in this case.

We wish to thank A. M. Clogston for stimulating

our interest in the problem of studying excited states in solids by paramagnetic resonance. We are grateful to D. Linn for his extensive experimental assistance and to Professor J. Brossel, A. Javan, W. B. Mims, H. E. D. Scovil, and Professor S. Sugano for helpful discussions.

[1]Varsanyi, Wood, and Schawlow, preceding Letter [Phys. Rev. Letters 3, 544 (1959)].

[2]S. Sugano and Y. Tanabe, J. Phys. Soc. (Japan) 13, 880 (1958).

[3]The principle of this method was also suggested independently by Professor J. Brossel.

[4]F. Bitter and J. Brossel, Phys. Rev. 86, 308 (1952).

[5]S. F. Jacobs, thesis, 1957, John Hopkins University (unpublished), earlier established the approximate $\cos\theta$ variation of the $\bar{E}(^2E)$ Zeeman pattern from the optical Zeeman spectrum. Our work confirms this with an order of magnitude greater accuracy characteristic of microwaves. We are grateful to Professor G. H. Dieke for making this work available to us.

[6]A. M. Clogston (private communication).

OPTICAL DETECTION OF PARAMAGNETIC RESONANCE IN CRYSTALS AT LOW TEMPERATURES

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(Received November 12, 1959)

Paramagnetic resonance absorption has been extensively used to determine the structure of the ground state of paramagnetic ions in different crystal fields. As is well known, many absorption and fluorescence spectra of ions in a crystal lattice show very sharp optical lines besides the usual broad bands. The Zeeman effect of these lines has been observed in some cases, and the components are often strongly polarized.

A method of detection of magnetic resonance in the fluorescent state which utilizes the selective reabsorption of the components of the fluorescent radiation at low temperatures has been described in the preceding Letter.[1] We wish to discuss extensions of this method to other cases which may arise, as well as to indicate where the more conventional double resonance[2] techniques may be applied to the study of paramagnetic ions in crystal lattices. In addition, we want to point out that optical detection of magnetic resonances in the ground state may have some merits of its own.

The first step in doing resonance in an excited state is to obtain a population difference between the Zeeman substates. We will use the case of ruby to illustrate the different possibilities. Referring to Fig. 1 of Varsanyi, Wood, and Schawlow,[3] two cases may arise:

(A) Thermalization is fast.—This we feel will be the most common case. It is what happens in ruby, i.e., the Boltzmann distribution is reached between (a) and (b) before the atoms radiate. The fluorescent state can be reached in any convenient way and one can rely on thermal relaxation to achieve the population difference. Absorption of light in any of the broad bands is particularly convenient because it can be filtered out at detection and need not come from a preferred direction.

(B) Thermalization is slow.—In this case, a population difference between the Zeeman levels of the excited state can be achieved, just as is done in gaseous double resonance experiments, by pumping with polarized resonance light. However, in a solid at low temperatures and high enough fields, one can even use unpolarized resonance radiation, because the lowest Zeeman level of the ground state is far more populated than the others, so that absorption will populate level (a) more than level (b).

Having obtained a population difference between the Zeeman levels of the excited state, the next step is to detect the change in this population on passing through magnetic resonance by observing the fluorescent light. At low temperatures selective reabsorption may be utilized as shown in the preceding Letter.

At temperatures very much above 4°K, however, selective reabsorption will not occur. In addition, selective reabsorption will be absent from a fluorescent line whose width is greater than the total Zeeman splitting of the ground state. In these cases, it follows from the transition probabilities shown in Fig. 1 of reference 3, and as explained in the preceding Letter, that the total light output is independent of the popula-

tion difference in the upper state and so will be unaffected by microwave transitions in the excited state. However, a microwave transition can nonetheless be detected by comparing the ratio of right circular (R) to left circular (L) light emitted in fluorescence; in particular (R) light will increase at resonance. The same thing will happen for all Kramers doublets. There is the experimental difficulty of looking along the direction of the field, at high fields where the Boltzmann factor is favorable. Moreover, the crystal must be strain free so as not to depolarize the light; but the method works even when the components of the optical Zeeman pattern overlap.

In studying resonance in the excited state by the selective reabsorption method, ground state resonances will often show up also, as they did in ruby, due to the change in population of the absorbing levels arising from the microwave resonance. This may be confusing under some circumstances. A way to see only the excited state is to operate with a ruby so dilute that no reabsorption takes place, and observe its fluorescence through a selectively absorbing ruby outside the rf field, but in the same magnetic field and at the same low temperature.

At liquid helium temperatures, optical detection of magnetic resonance in the ground state can be accomplished in several ways. The change of paramagnetic to diamagnetic Faraday effect has been used previously.[4] The absorption of circularly polarized light may be used, since as is seen from Fig. 1 of reference 3, component (a) is more absorbed, i.e., circularly left light is absorbed in the ruby 6934A line, to a greater extent than other polarizations. Resonance in the ground state between level 1 and any other will increase the amount of transmitted left light. One can operate at low fields. The light source may have "broad line" characteristics, but the light must travel along the field.

The same absorption method will apply to linearly polarized (σ or π) 6934A light, traveling perpendicular to the magnetic field, or even in the absence of a field.[5] However, with the condition just defined, transitions $-\frac{1}{2}\rightarrow+\frac{1}{2}$ and $-\frac{3}{2}\rightarrow+\frac{3}{2}$ will not appear, as seen from the optical transition probabilities (although they should appear if H were not along the optic axis). They can be observed with a suitable "narrow line" light source, emitting the Zeeman components with unequal intensities. This last case requires that the Zeeman components of the line be well separated and that fairly high fields be used.

Optical detection of ground state resonances could prove useful in many cases. For example, many satellite lines have been seen in the optical spectrum of Cr^{3+} in Al_2O_3 and MgO which are attributed[6] to Cr^{3+} pairs, as well as to an added axial field component due to charge compensation in the case of MgO. Such pairs and centers have indeed been identified by standard paramagnetic resonance techniques.[7] Therefore, by doing double-resonance type experiments on these optical satellites in such a way that only ground-state transitions are observed, a correlation can be made between the particular optical satellite and the type of center with which it is associated. In addition, optical detection of ground-state resonances will be helpful in unraveling unidentified paramagnetic resonance spectra which are associated with different types of centers; for, by studying the ground-state resonances of a particular optical satellite, one selects only that part of the total paramagnetic resonance spectrum associated with only one type of center.

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[1]Geschwind, Collins, and Schawlow, preceding Letter [Phys. Rev. Letters 3, 545 (1959)].

[2]F. Bitter and J. Brossel, Phys. Rev. 86, 308 (1952); A. Kastler, J. Opt. Soc. Am. 47, 460 (1957).

[3]Varsanyi, Wood, and Schawlow, this issue [Phys. Rev. Letters 3, 544 (1959)].

[4]J. M. Daniels and H. Wesemeyer, Can. J. Phys. 36, 406 (1958).

[5]I. Wieder, Phys. Rev. Letters 3, 468 (1959).

[6]Schawlow, Wood, and Clogston, Phys. Rev. Letters 3, 271 (1959).

[7]J. E. Wertz and P. Auzins, Phys. Rev. 106, 484 (1958); J. H. E. Griffiths and J. W. Orton, Proc. Phys. Soc. (London) 73, 948 (1959); private communications from M. Peter and from J. C. Gill.

SATURATION OF PARAMAGNETIC SPINS BY 13-Mc/sec ULTRASONIC PHONONS*

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(Received October 19, 1959)

Experiments have been conducted at 4.2°K with the object of saturating spin populations in various paramagnets through the use of 13-Mc/sec sound waves. Differences in energy level population were monitored by paramagnetic resonance equipment that included a Pound-Watkins oscillator followed by a narrow-band amplifier and a phase-sensitive detector, with dc and 50-cps modulating fields provided by Helmholtz coils. (The signal S is thus the slope of the imaginary part of the paramagnetic susceptibility.) The phonon source was an X-cut quartz crystal, cemented to the paramagnet with vacuum grease and driven by a 10-volt signal generator. The input impedance at low temperature was measured with an rf bridge; we were thus able to calculate the power input and to check the acoustical contact provided by the grease joint. With the assumption that sound radiation into the surrounding helium bath is the dominant loss mechanism, the phonon relaxation time was $\sim 10^{-4}$ sec, which yields a maximum phonon energy density of ~10 ergs/cm³ at a power input of ~0.3 watt. Direct electric pickup between the phonon generator and the oscillator tank coil was confined to a region about 0.05 Mc/sec wide, so that no measurements were made with phonon frequency exactly on spin resonance. In all cases in which an effect was observed, we repeated the experiment, using paper as a phonon barrier to ensure that phonons were indeed the source of the effect.

The first experiment was performed on ruby having a linewidth of 40 Mc/sec.[1] This substance obeys quadrupole selection rules,[2,3] and it is possible to show that if the phonon energy density is ~10 ergs/cm³, and the phonon frequency is $\sim 10^7$ cps, then the signal saturation, S/S_0 (which is the ratio of signal with phonon power on to signal with phonon power off), is equal to unity to within one part in 10^8 for a forbidden transition; and that for an allowed transition, S/S_0 is approximately 1/60. This means that acoustic saturation should be negligibly small for the low-field $\pm\frac{1}{2}$ Kramer's doublet. The measured value in this case was $S/S_0 = 1 \pm 0.01$ which is in agreement with theory within the accuracy of the experiment. On the other hand, saturation should be easily observable between the $+\frac{3}{2}, -\frac{1}{2}$ levels (transition allowed) where these levels nearly cross over. An acoustic saturation experiment with $+\frac{3}{2}, -\frac{1}{2}$ levels is now in progress.

It was predicted theoretically that because of the very small zero-field splitting in Cr^{+++}-doped MgO, the saturation should be huge ($S/S_0 \sim 10^{-7}$). The experimental results for a crystal with 10^{19} Cr^{+++} ions/cm³ are shown in Fig. 1. As expected, S/S_0 decreases with increasing phonon power and is maximum when phonon frequency, ν_p, is equal to the spin-resonance frequency, ν_γ. However, $S/S_0 \sim \frac{1}{2}$, which is 10^7 times smaller than theory predicts, and the bandwidth (which should be approximately the spin linewidth, 10 Mc/sec) is too large. To determine, if possible, an upper limit to the bandwidth, we ran an additional experiment at $\nu_\gamma = 195$ Mc/sec, using a different spectrometer. This produced the peculiar result shown in the dotted curve of Fig. 2. For comparison, curves are given for S/S_0 versus

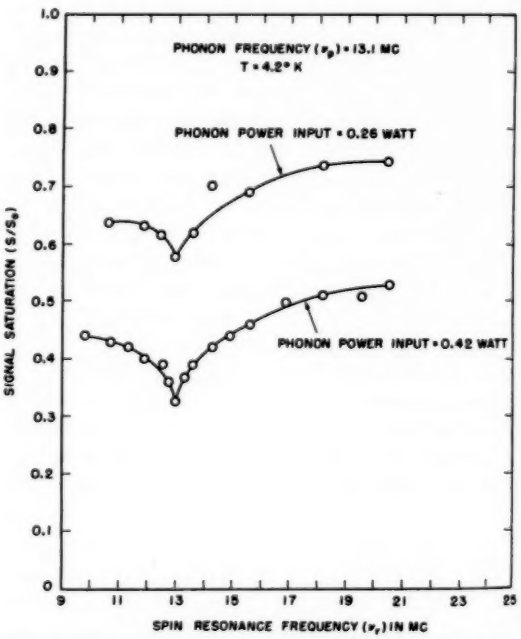

FIG. 1. Acoustic saturation vs spin-resonance frequency in MgO doped with 10^{19} Cr^{+++} ions/cm³.

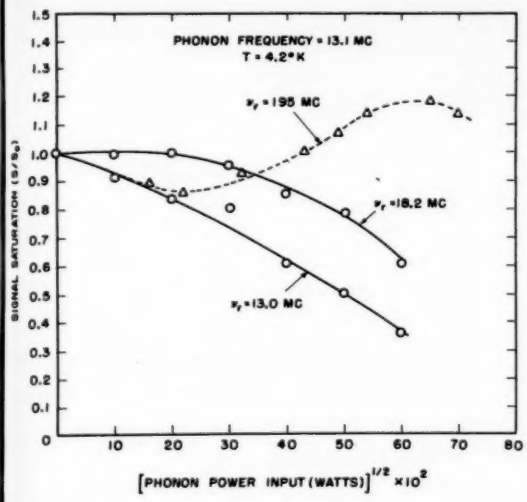
PHONON FREQUENCY = 13.1 MC
T = 4.2°K
ν_γ = 19.5 MC
ν_γ = 18.2 MC
ν_γ = 13.0 MC
SIGNAL SATURATION (S/S$_0$)
[PHONON POWER INPUT (WATTS)]$^{1/2}$ ×10^2

FIG. 2. Acoustic saturation vs square root of the phonon power in MgO doped with Cr^{+++}.

the square root of the phonon power input at two lower frequencies. A possible explanation of some of these anomalies may be in the fact that the Cr^{+++} ion distorts the local lattice considerably[4]; this effect is nowhere taken into account by the theory.[2]

An apparent saturation was observed in a crystal of Brazilian quartz which had been given a 1.4×10^7-rad dose of γ rays in a Co^{60} source. With phonon power of approximately 0.2 watt, we found $S/S_0 = 0.4 \pm 0.05$, from $\nu_\gamma - \nu_p = -2.3$ Mc/sec to +7.5 Mc/sec, and $S/S_0 \approx 0.6$ at $\nu_\gamma - \nu_p$ =175 Mc/sec. This makes the bandwidth of the effect greater than 176 Mc/sec, which agrees with the result obtained by Jacobsen et al.[5] with microwave phonons. The approximate frequency independence of the effect here suggests that the phonons simply cause thermal heating of the crystal. However, to get the right order of magnitude, this requires the rather short acoustic phonon – thermal phonon relaxation time of $<10^{-4}$ sec; and a very low thermal conductivity ($\approx10^{-3}$ watt/cm-deg).

If thermal heating is indeed the cause of this effect, an even greater saturation should be seen in irradiated fused quartz because its thermal conductivity is reported lower than that of natural quartz. However, this postulate does not seem tenable, since an experiment performed on irradiated fused quartz yielded $S/S_0 = 1.15 \pm 0.03$ at phonon power of ≈ 0.2 watt. There was some evidence of a slight decrease in linewidth accompanying the increase in line height It should be noted that in a slope measurement the maximum slope is reciprocally proportional to the square of the linewidth; hence these two effects tend to cancel each other.

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†Present address: Royal Institute of Technology, Stockholm, Sweden.

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BARDEEN-COOPER-SCHRIEFFER THEORY OF SUPERCONDUCTIVITY IN THE CASE OF OVERLAPPING BANDS

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The purpose of this note is to point out an extension of the Bardeen-Cooper-Schrieffer theory of superconductivity[1] to the case where two bands with more or less itinerant electrons overlap. Such a situation arises in the transition elements, in which $s-d$ scattering supposedly contributes considerably to the resistivity in the normal state.[2] We discuss here the corresponding result for the superconducting state in some of the transition elements, though one may speculate if such effects do not also occur in some cases of superconductors with $s-p$ bands.

By analogy with the BCS theory, we write down the electron portion of the Hamiltonian resulting from emission and reabsorption of a phonon. This virtual process may take place in four ways, since an s or a d electron may emit the phonon, and then, an s or a d electron may reabsorb it independently. The phonon involved must have a wave number equal to the difference in wave numbers of the two electrons, both of which must be in the same vicinity of the Fermi level as in the BCS theory. For an $s-d$ process the phonon involved must therefore have a certain minimum momentum, the same minimum as in the corresponding resistivity theory.

The portion of the Hamiltonian that is amenable to formation of ss and dd pairs now takes the form

$$H=\sum_{\mathbf{k}\sigma}\epsilon_{\mathbf{k}s}c_{\mathbf{k}\sigma}^{*}c_{\mathbf{k}\sigma}+\sum_{\mathbf{k}\sigma}\epsilon_{\mathbf{k}d}d_{\mathbf{k}\sigma}^{*}d_{\mathbf{k}\sigma}-\sum_{\mathbf{k}\mathbf{k}'}V_{ss}c_{\mathbf{k}\uparrow}^{*}c_{-\mathbf{k}\downarrow}^{*}c_{-\mathbf{k}'\downarrow}c_{\mathbf{k}'\uparrow}-V_{dd}\sum_{\mathbf{k}\mathbf{k}'}d_{\mathbf{k}\uparrow}^{*}d_{-\mathbf{k}\downarrow}^{*}d_{-\mathbf{k}'\downarrow}d_{\mathbf{k}'\uparrow}$$
$$-V_{sd}\sum_{\mathbf{k}\mathbf{k}'}(c_{\mathbf{k}\uparrow}^{*}c_{-\mathbf{k}\downarrow}^{*}d_{-\mathbf{k}'\downarrow}d_{\mathbf{k}'\uparrow}+d_{\mathbf{k}\uparrow}^{*}d_{-\mathbf{k}\downarrow}^{*}c_{-\mathbf{k}'\downarrow}c_{\mathbf{k}'\uparrow}),\qquad(1)$$

where $\epsilon_{\mathbf{k}s}$, $\epsilon_{\mathbf{k}d}$ are s- and d-band kinetic energies, and c^{*}, c and d^{*}, d the corresponding annihilation and creation operators. V_{ss}, V_{dd}, and V_{sd} are the averaged interaction energies resulting from phonon emission and absorption by $s-s$, $d-d$, and $s-d$ processes, minus the corresponding shielded Coulomb interaction terms. As in the BCS theory, we assume that the summations extend only over $\vec{\mathbf{k}}$ values (quite different $\vec{\mathbf{k}}$ values in the two bands) corresponding to energies within a distance $\pm\hbar\omega$ of the Fermi surface. ($\hbar\omega$ is of the order of the maximum available phonon energy.)

Following Bogoliubov,[3] we introduce the new operators e and f by the transformations

$$c_{\mathbf{k}\uparrow}=\cos(\theta_{\mathbf{k}}/2)e_{\mathbf{k}\uparrow}+\sin(\theta_{\mathbf{k}}/2)e_{-\mathbf{k}\downarrow}^{*};$$

$$d_{\mathbf{k}\uparrow}=\cos(\varphi_{\mathbf{k}}/2)f_{\mathbf{k}\uparrow}+\sin(\varphi_{\mathbf{k}}/2)f_{-\mathbf{k}\downarrow}^{*},$$

$$c_{\mathbf{k}\downarrow}=\cos(\theta_{\mathbf{k}}/2)e_{\mathbf{k}\downarrow}-\sin(\theta_{\mathbf{k}}/2)e_{-\mathbf{k}\uparrow}^{*};$$

$$d_{\mathbf{k}\downarrow}=\cos(\varphi_{\mathbf{k}}/2)f_{\mathbf{k}\downarrow}-\sin(\varphi_{\mathbf{k}}/2)f_{-\mathbf{k}\uparrow}^{*}.$$

The parameters θ,φ are determined by substituting for c and d in (1), and equating to zero the coefficients of $e_{\mathbf{k}}^{*}e_{-\mathbf{k}}^{*}$ and $e_{-\mathbf{k}}e_{\mathbf{k}}$, and similarly for the f terms. The resulting equations are

$$\epsilon_{\mathbf{k}s}\sin\theta_{\mathbf{k}}-[V_{sd}D+V_{ss}S]\cos\theta_{\mathbf{k}}=0,$$

$$\epsilon_{\mathbf{k}d}\sin\varphi_{\mathbf{k}}-[V_{dd}D+V_{sd}S]\cos\varphi_{\mathbf{k}}=0,\qquad(2)$$

with

$$D=\tfrac{1}{2}\sum_{\mathbf{k}}\sin\varphi_{\mathbf{k}}[1-2f_{d}(E_{\mathbf{k}d})],$$

$$S=\tfrac{1}{2}\sum_{\mathbf{k}}\sin\theta_{\mathbf{k}}[1-2f_{s}(E_{\mathbf{k}s})].\qquad(3)$$

Here $f_{s}(E_{\mathbf{k}s})$, $f_{d}(E_{\mathbf{k}d})$, respectively, denote the number of quasi-particles deriving from the s and d bands that are excited to energies $E_{\mathbf{k}s}$, $E_{\mathbf{k}d}$, respectively. These energies are

$$E_{\mathbf{k}s}=(\epsilon_{\mathbf{k}s}^{2}+A^{2})^{1/2},\quad E_{\mathbf{k}d}=(\epsilon_{\mathbf{k}d}^{2}+B^{2})^{1/2},$$

where

$$A=V_{sd}D+V_{ss}S,\quad B=V_{dd}D+V_{sd}S.$$

The self-consistency conditions for (2) and (3) give two simultaneous equations for A and B:

$$A[1 - V_{ss}N_sF(A)] = BV_{sd}N_dF(B),$$
$$B[1 - V_{dd}N_dF(B)] = AV_{sd}N_sF(A), \quad (4)$$

where

$$F(A) = \int_0^{\hbar\omega} d\epsilon \tanh\left[\frac{(\epsilon^2 + A^2)^{1/2}}{2kT}\right] \Big/ (\epsilon^2 + A^2)^{1/2},$$

and where N_s, N_d are the densities of states in the s and d bands near the Fermi level.

The transition temperatures are given by the quadratic

$$[V_{ss} + N_d(V_{sd}^2 - V_{ss}V_{dd})F(0)][V_{dd} + N_s(V_{sd}^2 - V_{ss}V_{dd})F(0)] = V_{sd}^2.$$

When this equation is solved for $F(0)$, and use is made of the BCS expression for $F(0)$, the transition temperature is found to be

$$kT_c = 1.14\hbar\omega \exp\left\{-\left[\frac{[V_{sd}^2/N_sN_d + \frac{1}{4}(V_{dd}/N_s - V_{ss}/N_d)^2]^{1/2}}{V_{sd}^2 - V_{ss}V_{dd}} - \frac{\frac{1}{2}(V_{dd}/N_s + V_{ss}/N_d)}{V_{sd}^2 - V_{ss}V_{dd}}\right]\right\},$$

and both A and B go to zero there. In the special case of interband scattering only ($V_{ss} = V_{dd} = 0$) one obtains the same transition temperature as BCS, with a state density $(N_sN_d)^{1/2}$, but, unless $N_s = N_d$, there are still two gaps. Figures 1 and 2 show the gaps for a variety of values of the parameters.

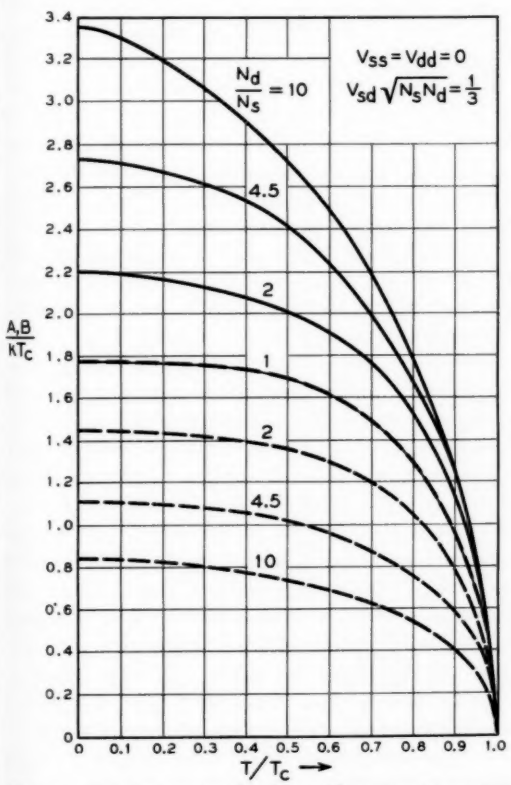

FIG. 1. The gap-pairs for $V_{ss} = V_{dd} = 0$ and various densities of state. The curves for V_{ss}, $V_{dd} \neq 0$ are very similar to those shown, except when $V_{sd}^2 \ll V_sV_d$.

These results may obviously be generalized to more complicated band structures. When there are n distinct Fermi surfaces in $\vec{k}$ space, the pair of equations (4) is replaced by the set

$$A_i = \sum_{j=1}^{n} V_{ij}A_jN_jF(A_j), \quad (n = 1, 2 \ldots)$$

determining the n energy gaps A_i. We suggest

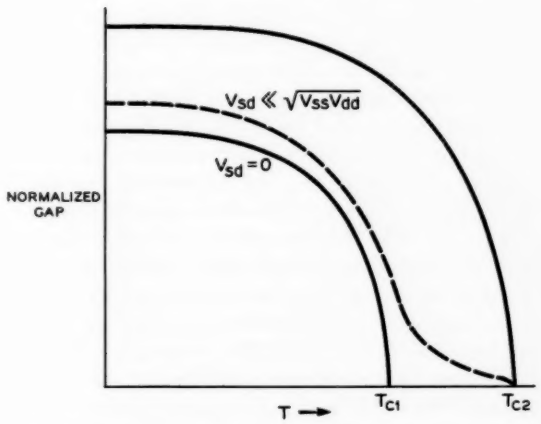

FIG. 2. When $V_{sd} = 0$, there are two transition temperatures. When V_{sd}^2 is finite but much less than $V_{ss}V_{dd}$, the lower transition temperature disappears in the manner shown.

these results as a possible explanation of the fine structure observed by Tinkham and co-workers[4,5] in their infrared absorption measurements in some superconductors. They may also partly account for the rules according to which maximal transition temperatures for s - d superconductors are observed at conduction electron concentrations corresponding to at least some of the maxima in the N_d curve. Even though the d electrons may not participate directly in the phenomenon of superconductivity ($V_d = 0$), the s electrons can benefit from the higher density of states in the d band.

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RESONANT ABSORPTION OF THE 14.4-kev γ RAY FROM 0.10-μsec Fe^{57}†

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(Received November 23, 1959)

We wish to report experiments on the resonant scattering of a recoil-free γ ray[1] which appears to be sharp enough to be used for an experimental determination of the "gravitational red-shift," as proposed in our recent note.[2]

Our initial work has been with the 14.4-kev γ ray of 0.10-microsecond Fe^{57}. Although we first worked with a source of the 270-day parent Co^{57} extracted from an iron foil kindly irradiated for us with the deuteron beam at the MIT cyclotron, an intense background of Co^{56} rendered that source poor for our purposes. Most of our work has been with Co^{57} obtained commercially.

About 50 microcuries of Co^{57} was electroplated together with added iron onto one face of a one-centimeter square of thin Armco iron.

Initial studies of the absorption of a 0.001-in. thick iron foil at temperatures of liquid nitrogen and at room temperature indicated that the desired resonant absorption was present, that the ratio of about 3:2 of the magnitudes at the two temperatures was in reasonable agreement with theory, but that the absorption was small and the line was broad compared to its natural breadth. In these experiments crude 60-cycle magnetic vibrators were used to destroy resonance and to observe the line widths. The increase in intensity available by the use of low temperatures is so small that we henceforth operated at room temperature, in the interest of stability.

The supposition that the hyperfine structure splittings of the ferromagnetic source and absorber were not fully equivalent led us to try heat treatments of the source and absorber foils. A dramatic improvement resulted after the source had been held at 950°C for an hour, which treatment was expected to result in diffusion of the cobalt, if it were retained on the surface initially, into the lattice a mean distance of about 3×10^{-5} cm, or 1000 lattice spaces. We have discovered that there was probably about 0.1 mg of stable cobalt carrier present in our source which may be important in making such treatment necessary. With the absorber foil first used, which was found to contain 3% silicon, replaced by one rolled from Armco iron to 11.5 mg/cm^2 thickness, and annealed, the line shown in Fig. 1 was obtained.

These data represent counts above background of the 14.4-kev γ ray as made with a scintillation spectrometer, using a 0.040-in. by $\frac{3}{4}$-in. NaI(Tl) crystal[3] and a single-channel pulse-height analyzer set to accept most of the full-energy peak.

All but about fifteen percent of the counts in the channel arose from the γ ray, from evidence obtained with absorbing foils. Each point is based on about 2.3×10^5 counts shared equally between conditions with the source fixed and with it moving toward and away from the absorber at constant speed. The motion was produced by a moving-coil magnetic transducer on which the source was cemented and which was supplied with a ten-cycle-per-second triangular waveform of current of adjustable amplitude.

The resonant absorption is halved by a Doppler speed of $|v_{1/2}| = 0.017$ cm/sec (which, incidentally,

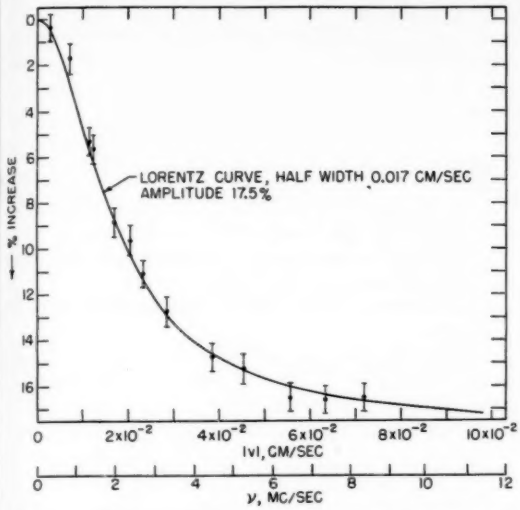

FIG. 1. The percentage increase in intensity of the 14.4-kev γ ray as a function of the absolute value of the velocity of the source. A velocity of 0.01 cm/sec corresponds to a frequency displacement of 1.16 Mc/sec.

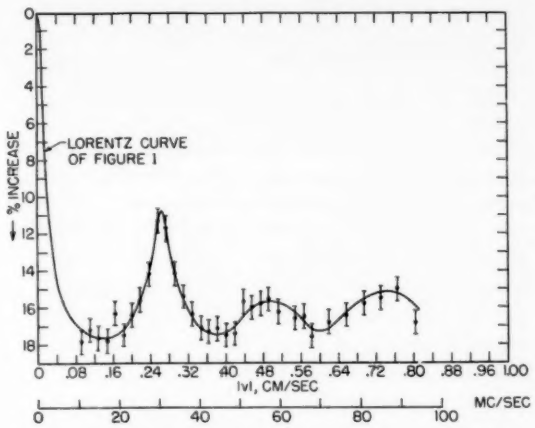

FIG. 2. The increase in intensity for velocities large enough to show hyperfine structure. There appear to be three principal satellites which probably correspond to the hyperfine structure interaction of the 0.10-μsec metastable, spin 3/2, nucleus with the internal effective magnetic field.

corresponds to only 0.0009 cm peak-peak amplitude at 10 cps). This is to be compared to 0.0095 cm/sec to be expected from energy and lifetime considerations for a "thin" absorber if no broadening exists other than from the lifetime. We are not certain that our initial difficulties with effects from the surface or the cobalt carrier are entirely eliminated and we are inclined to attribute the residual broadening by a factor of approximately two at least partly to such causes.

Our experimental width at half-height is approximately 10^{-12} times the velocity of light and represents a 100-fold reduction compared to the example reported by Mössbauer[1] and others.[4,5]

It is known that hyperfine splitting exists in ferromagnetic metals. The 14.4-kev γ ray is thought to be a magnetic dipolar transition and, with an excited state spin of 3/2 and ground-state spin of 1/2, the radiation ought to consist of six hyperfine components and the absorber should have a matched set of six lines. With appropriate Doppler speeds at the source, displacements should be found that produce partial overlaps of the lines, yielding a form of hyperfine satellites. In a limited study, we have found some structure we believe to be of this type. The results are shown in Fig. 2. We do not wish to take the space here to give the straightforward theoretical description of the hyperfine structure which we will do in a more complete report later.

There appear to be three satellite lines, the innermost occurring at a speed $|v| = 0.26$ cm/sec, corresponding to a frequency shift of 30.5 Mc/sec. The g factor of the ground state of Fe^{57} is known to be small,[6,7] although 20 Mc/sec of splitting has been observed in stable Fe^{57} as an impurity in silicon.[8] If the ground-state splitting is negligible—or contributes only to the line widths observed—the three satellite lines of integrated intensities 3/4, 1/2, and 1/4 times that of the center line would fall at Doppler frequencies equal to one, two, and three times the Larmor frequency of the spin 3/2 excited state in the effective classical magnetic field at the nucleus in the ferromagnet. According to this interpretation the Larmor frequency of the excited state is about 30 Mc/sec and its magnetic moment is large compared to that of the ground state. The breadth of the satellites may be caused in part by inconstancy of the speed of the transducer during a modulation cycle. We are engaged in improving this as well as in processing a source of much larger activity in the interest of gathering more detailed data. Until we know the details of the hyperfine structure more fully, we cannot make an exact comparison of the magnitude of the scattering with theory because the cross sections depend upon the degree of resolution of the lines.

We are now confident that we can perform the gravitational experiment inside the laboratory

using this γ ray from Fe^{57}. With the line width we have found, a measurable shift of the line center is predicted by the principle of equivalence[9] for the height difference available to us inside this laboratory.

With a source of limited strength, statistical fluctuations decrease the definition of the line, owing to decreased counting rates, in a way that just compensates, assuming the inverse square law to apply over the path, the linear increase in shift as the height difference between source and absorber is increased. Use of very large vertical distances do not appear to offer much increase in precision.

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RECOILLESS RESONANCE ABSORPTION OF GAMMA RAYS IN Fe^{57}

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(Received November 23, 1959)

The recent observation that at low temperatures gamma-ray absorption and emission could take place without recoil,[1,2] has led to the suggestion that it might be of use in measuring hyperfine splittings of gamma-ray lines caused by effective magnetic fields acting on the magnetic moment of the nucleus.[2] This technique would be of particular interest in ferromagnets and antiferromagnets where other methods of measuring these fields are severely limited.

A particularly favorable case for recoilless emission or absorption is in the decay of the 14-kev first excited state of Fe^{57}. Here the Debye-Waller factor predicts that at room temperature 63% of the gamma rays should be emitted without recoil. A source of Co^{57} has been prepared by bombarding a 0.0005-in. Fe foil by 4-Mev deuterons from the Harwell Van de Graaff accelerator. An absorber of a similar Fe foil (containing 2.2% Fe^{57}) was used with a xenon-filled proportional counter to detect the 14-kev radiation. The source was mounted on the diaphragm of a loud speaker. The number of gamma rays emerging from the absorber with the source moving with a velocity large compared to the width of the line was approximately 20% larger than the number of gamma rays with the source stationary. This can be compared with the 1-2% absorption which has been reported at low temperatures previously.[1,] This is approximately in agreement with the effect expected from the above Debye-Waller fac tor assuming the line to be split by the hyperfine interaction (if the latter were zero the effect would have been several times larger). The effect could be increased by using enriched Fe. Cooling the source to liquid air temperatures would increase the effect only by about 40%.

Since the magnetic field in Fe is expected to be approximately 200 kilogauss, one would expect the hyperfine splitting to be several times the line width of 4.5×10^{-9} ev even for the ground state magnetic moment of 0.05 nuclear magneton. The excited state presumably will have a larger magnetic moment and thus give rise to even larger splittings. It should be very easy to introduce Fe^{57} into various alloys and compounds and obtain relative values of the hyperfine fields. These could also be measured easily as a function of temperature. Apparatus for such experiments is under construction.

It has been suggested by T. E. Cranshaw that the size of the absorption and the narrowness of the line makes this an ideal case for measuri

the gravitational red shift of a photon. At a height of 20 meters this would produce a shift in the energy of the gamma rays which would be 1% of the width. With a one-curie source of Co^{57}, this effect would be measured with 10% accuracy, in 20 hours of counting. An experiment to measure this is also under way in collaboration with Dr. Cranshaw and awaits the successful preparation of a source of sufficient intensity.[3]

*John Simon Guggenheim Fellow on leave from Argonne National Laboratory, Lemont, Illinois.

[1]R. L. Mossbauer, Z. Naturforsch. 14a, 211 (1959). Craig, Dash, McGuire, Nagle, and Reiswig, Phys. Rev. Letters 3, 221 (1959).

[2]Lee, Meyer-Schutzmeister, Schiffer, and Vincent, Phys. Rev. Letters 3, 223 (1959).

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NUCLEAR FRAGMENTS PRODUCED IN THE HEAVY ION BOMBARDMENT OF ALUMINUM*

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(Received November 13, 1959)

We have observed reaction products ranging from lithium to fluorine produced by bombarding aluminum with 160-Mev oxygen ions. The data were taken by means of a plotting oscilloscope which recorded the energy and rate of energy loss of each particle. The energy detector was a CsI scintillator and the dE/dx detector was a short proportional counter. A photographic record of 2000 particles is shown in Fig. 1. Each spot represents a detected particle. Its location on the photograph is determined by its energy and its rate of energy loss. Each curved line represents particles of the same Z, since dE/dx is approximately proportional to MZ^2/E. This simple relationship is modified by the dependence of the pulse-height response of CsI on the type and energy of particle[1] as well as by the dependence of the effective charge of the particle on energy. In principle each curve could be further separated into isotopes. The lack of separation may be due to insufficient detector resolution but also may be due in these photographs to the ratios of yields of different isotopes, i.e., an isotope in large yield may obscure small yields of adjacent isotopes.

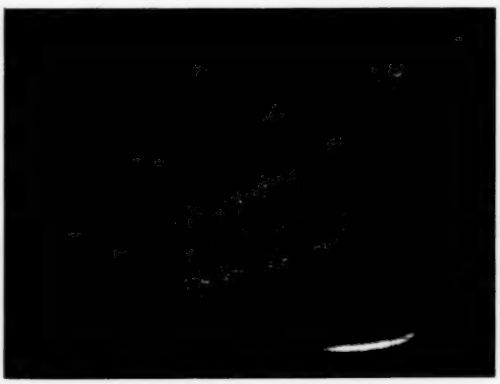

FIG. 1. Photographic record of nuclear fragments emitted at 15° in the bombardment of Al by 160-Mev oxygen ions. E increases to the left and dE/dx increases upward. The three most prominent lines in the center are due to oxygen, nitrogen, and carbon fragments; the solid line at the bottom is due to helium; also visible but less conspicuous are lines due to lithium, beryllium, boron, and fluorine and a few heavier fragments.

The energy spectrum and angular distribution in the laboratory for each element can be determined by counting and measuring the CsI pulse-height coordinates of spots on photographs. Photographs to be counted are limited to about 200 particles to reduce the possibility of overlapping spots.

Preliminary results obtained from 10 photographs at each angle of observation are shown in Figs. 2 and 3. Figure 2 shows the total number of particles emitted of each element (independent of energy) as a function of laboratory angle. Figure 3 shows the energy spectra of emitted carbon fragments in the center-of-mass system at various center-of-mass angles. The center-of-mass transformation was made assuming that the carbon fragments were of mass 12.

Table I gives the total cross section for the production of each element obtained by numerical integration of the yield as a function of the labor-

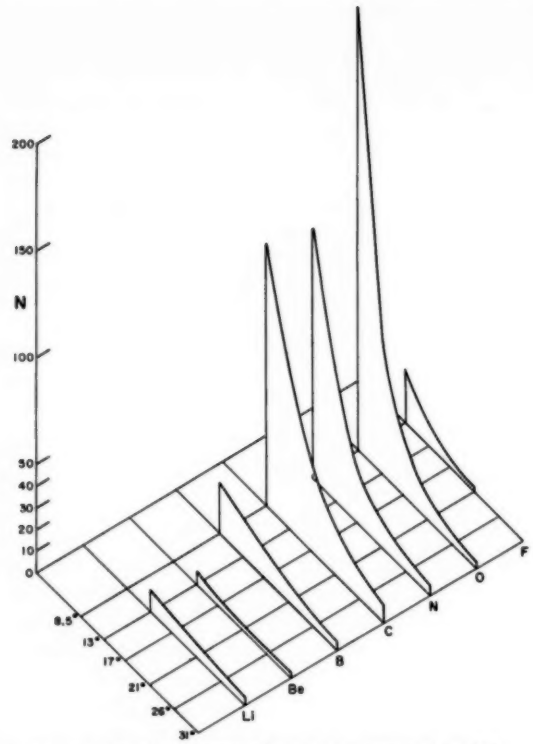

FIG. 2. Total numbers of particles per unit solid angle versus laboratory angle of observation.

atory angle. The cross sections for Li and Be are minimum values since the angular distributions are rather flat and larger angles may make appreciable contributions. Relative cross sections for B, C, N, and F are estimated to be accurate to ± 20% while the errors on the absolute cross sections are estimated to be about ± 50%. The value for the oxygen cross section depends on how the separation of elastic from inelastic events is made.

Table I. Total cross sections in millibarns for production of nuclear fragments in the bombardment of Al by 160-Mev oxygen ions.

Element	σ (mb)
Fluorine	30
Oxygen (inelastic)	150–300
Nitrogen	170
Carbon	210
Boron	60
Beryllium	>20
Lithium	>30

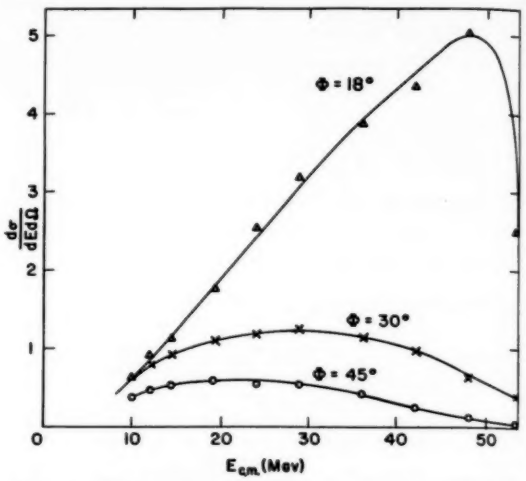

FIG. 3. Differential cross section in millibarns per Mev per steradian for carbon fragments in the center-of-mass system.

Fragments produced in the bombardment of a polyethylene target by 160-Mev oxygen ions have also been observed by visual inspection of pictures similar to Fig. 1. Qualitatively the spectra and relative numbers of particles in this reaction are very similar to those of the oxygen on aluminum reaction except for an obvious difference in elastic scattering at the smallest angles of observation.

We interpret these results in the following way:

1. The relatively flat angular distribution of Li products as well as their low cross section (an order of magnitude less than that of α particles observed, but not shown here) suggest their production by evaporation from a compound nucleus.[2] A similar argument applies, but less strongly, to the Be products.

2. The very large cross sections for the heavier fragments definitely rule out evaporation processes even without considering their angular distributions.

3. Comparison with radiochemical data[3] shows that the radiochemically observable products form only a small fraction of the total yield for fragments lighter than the projectile. The thick-target C^{11} cross section is about 1% of our observed carbon fragment cross section at 160 Mev. Similarly the N^{13} cross section is 2 or 3% of our observed nitrogen fragment cross section. This indicates that the more stable isotopes are produced with much greater cross section than

the previously observed radioactive products.

4. The angular distributions of carbon fragments are strongly peaked at forward angles in the center-of-mass system. This is particularly true for those fragments whose velocity approaches that of the incident oxygen ion. These observations suggest that "impact disintegration" or "stripping" of the projectile plays a large part in the production of fragments lighter than the projectile. This is also supported by studies of stars produced in nuclear emulsions by energetic carbon[4] and nitrogen[5] ions.

5. The fluorine fragment cross section, although much lower than that for C, N, and O, is still rather large compared to observed cross sections for nucleon transfer processes.[6] The fluorine fragments are also of conspicuously lower energy than the C, N, and O fragments. Thus it is suggested that the fluorines may be produced by breakup of target nuclei although an appreciable part of the cross section may still be due to nucleon transfer to the projectile.

6. The qualitative lack of dependence of the products of high yield on the nature of the target indicates that processes involving breakup or stripping of the projectile predominate in these observations.

7. The observed cross section for fragmentation represents a large fraction of the geometric cross section for this reaction. This may be related to the high angular momentum involved in heavy-ion reactions (the rms angular momentum in this reaction is about 30$\hbar$). Calculations using the liquid drop model of the nucleus indicate that the compound nucleus may not be formed in collisions involving such high angular momentum.[7]

More detailed studies of specific reaction products will be made. It is hoped that the isotopes of some of the products may be separated using this experimental technique.

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*This work has been supported by the U. S. Atomic Energy Commission.

†National Science Foundation Undergraduate Summer Research Grant.

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DISTRIBUTION OF PARTIAL RADIATIVE WIDTHS IN Cu^{59} FOLLOWING PROTON CAPTURE IN Ni^{58}

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In view of recent interest[1,2] in the distribution of partial radiative widths, it seems appropriate to publish some preliminary results from analysis of radiative capture of protons in Ni^{58}. In a previous Letter,[3] a distribution of total radiative widths was given; in addition, using two 5-in. diam×6-in. long NaI detectors, we have obtained information on partial radiative widths by taking spectra of the γ radiation at 0° and 90° to the proton beam. Measurements have been made on 48 of the larger, better separated, resonances.

If the intense components of the spectra are predominantly dipole, the ratio of yields at 0° and 90° gives a strong indication of the spin of the resonant state in Cu^{59}. The estimated radiative widths for emission of radiation of energy 5 Mev are: $E1$, 2 ev; $M1$, 0.04 ev; $E2$, 7×10^{-4} ev; $M2$, 1.5×10^{-5} ev. These estimates are derived from Blatt and Weisskopf,[4] taking 60 kev as an estimate of the mean spacing of levels in Cu^{59} of given J at the excitation energy concerned[5] and 5 Mev for the "single-particle spacing" D_0. Since we are dealing with resonances for which the total radiative widths fluc-

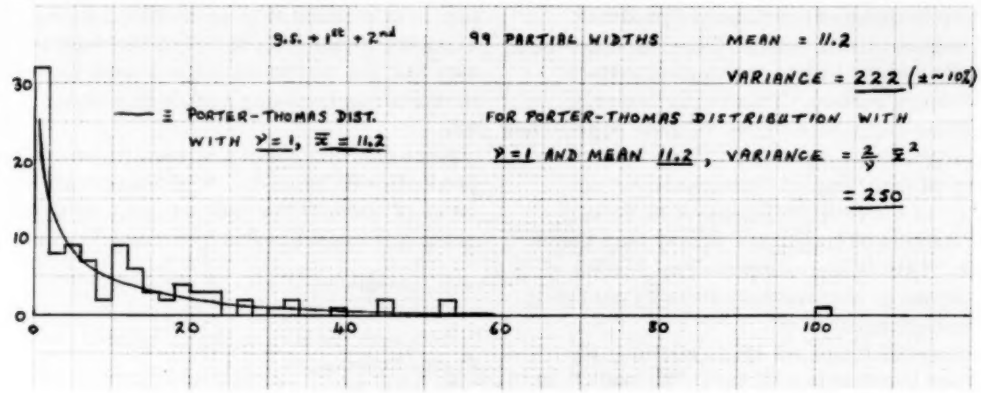

FIG. 1. Frequency distribution of partial radiative widths in Cu^{59}. The radiative widths are referred to a particular transition as 100 units—see text; the ordinate is the number of radiative widths, in an interval of 2 such units, obtained from 48 resonances.

tuate between 0.01 and 2 ev and are concerned with a nucleus near double closed shells for which enhancement of $E2$ radiation is unlikely, it is highly probable that the larger partial widths are pure $E1$ while the smaller ones may be pure $E1$, or $M1$ with an admixture of $E2$ of perhaps up to 20% in amplitude.

So far we have been able to infer the spins of 23 of the levels in Cu^{59}, and for these we can distinguish between transitions unobserved because of dipole selection rules and transitions known to be dipole but below the experimental threshold of observation. We present in Fig. 1 the combined distribution of partial widths of transitions to the ground state or the first or second excited states (at 0.492 and 0.908 Mev). The data consist of all detected transitions to one or other of these three states augmented by the above-mentioned unobserved, but definitely dipole, transitions. The widths have been corrected for dependence upon γ-ray energy and for dependence of level density upon excitation by normalizing to the point at 100 units in the plot, which corresponds to a partial width of 1 ev and an energy (and excitation) of 5.25 Mev. The g factor has been ignored and also the dependence upon J of the level density correction; for a level density proportional to $(2J+1)$ the two factors cancel.

The distribution is seen to agree closely in shape with a Porter-Thomas[6] distribution having $\nu=1$ and has the appropriate relationship between mean and variance. The close agreement may be partly fortuitous because of the following points:

(1) $E1$ and $M1$ transitions have not been separated out and this may account for the preponderance of small transitions.

(2) The selection of transitions is not free from bias since analysis is easier for spectra having a strong transition to ground. This results in a lack of near-zero radiative widths to ground and, because of difficulty in seeing feeble lines in the presence of more intense neighbors, a loss of near-zero transitions to the two excited states. This latter loss is accounted for completely when the spin of the resonant state is known.

(3) The level density may not be proportional to $(2J+1)$, so combining observations without regard to spin will distort the true distribution.

It is hoped to determine more completely the spins and parities of states in Cu^{59} by elastic scattering of protons in Ni^{58}, in which case information will become available on all three issues. Even at this stage of analysis, the data presented here and in our previous communication indicate that partial radiative widths are widely distributed and are consistent with the theoretically predicted distribution. This conclusion contrasts with that inferred from other data, referred to above,[1] for neutron capture in a heavy element.

One of us (J.H.C.) is indebted to Dr. E. Bretscher and Dr. E. B. Paul for the facilities made available to him while visiting Harwell.

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MEASUREMENTS ON THE $\pi^{\pm}$-p TOTAL SCATTERING CROSS SECTIONS IN THE ENERGY RANGE OF 0.4 to 1.5 Bev

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Studies on the photoproduction of π mesons in hydrogen have shown the probable existence of a new π-nucleon "resonance state" at a total energy (proton mass deducted) of $E^*-m_p \simeq 570$ Mev[1] in the center-of-mass system. The π^--p scattering cross sections[2] appear to confirm the existence of such a state. Recent scattering measurements[3] gave the position of this state at 615 Mev which is slightly different from that obtained in the photoproduction results. These same measurements also show a second maximum in the π^--p total scattering cross section at around 780 Mev.

We have undertaken to make absorption measurements of $\pi^{\pm}$ in hydrogen with a highly energy-selected π beam. The mean energy of the π beam is determined to an accuracy of $\pm 1\%$ and the energy resolution is $\pm 1.8\%$ including multiple scattering effects in the window and counters (the resolution is $\pm 0.9\%$ not including the multiple scattering effects).

The results obtained in the present experiment confirm the existence of the two maxima in the π^--p total cross sections but the energy values for these maxima differ appreciably from the previous results.[3] The absolute values of the cross sections in the region of the peaks obtained in the present experiment are also considerably higher than those obtained in the previous measurements.

The π beam is obtained from a carbon target which is placed in one of the straight sections of the Saclay proton synchrotron at an angle of 18.5° from the direction of the accelerated proton beam. The π beam is then momentum analyzed and focussed on to a liquid hydrogen target. The direction of the π is defined by a counter telescope to about $\pm 0.5°$ and within a circular area of a diameter of 6 cm at the entrance of the target. The separation of π^+ from protons was achieved by the time-of-flight method. The hydrogen target is 40 cm long and it subtends an angle of 6° at its center by the last counter (15 cm in diameter) of the telescope at a distance of 72 cm. The attenuation of the beam by the empty target does not exceed 20% of that by the filled target.

The energy of the π is determined by the wire method in terms of current values in the analyzing magnet. In order to avoid possible errors due to hysteresis effects when reversing and changing the field, a Hall-effect gauge is provided to monitor the magnetic field constantly. A magnetic shield at the exit of the beam from the straight section of the proton synchrotron serves to eliminate any effect on the π beam due to the fringing field of the machine, thus assuring a symmetry of the beam for the two polarities. The energy of the π is measured directly as well as indirectly by the following methods: (a) by a differential range curve of the protons of 800 Mev/c; (b) by differential range curves of π^+ of 400 and 500 Mev/c and π^- of 400 Mev/c; (c) by a determination of the velocity of the protons of 800 Mev/c by the time-of-flight method. All these measurements are in agreement within $\pm 1\%$. We have adopted the energy values obtained by the wire measurement taking into account the corrections due to energy losses in the counters and in the air.

The μ-meson and electron contamination in the beam have been determined at six different energies by means of a gas Čerenkov counter employing CO_2 or C_2H_4, the details of which will be described elsewhere. These contaminations amount to about 30% at 400 Mev and they drop to around 7% at 1 Bev. The other corrections which have been taken into account here are as

follows: (a) correction due to accidentals in the background $\lesssim 1.1\%$; (b) correction due to elastic scattering of π or proton in the last counter $\lesssim 1.7$ mb; (c) correction due to inelastic scattering in the last counter $\lesssim 0.5$ mb; (d) correction due to scattering in air in the empty target $\lesssim 0.5$ mb.

The correction due to elastic scattering has been estimated by using the scattering cross-section values in the forward direction which are deduced from the dispersion relations[2] and which are in agreement with the experimental results.[4] The correction due to inelastic scattering is estimated based on experimental results[2] and assuming an isotropic distribution in the center-of-mass system.

The results are given in Fig. 1 and in Table I.

We wish to express our thanks to the staff of

Table I. Total scattering cross sections.

Pion kinetic energy[a] (lab) (Mev)	Corrections: For beam contamination[b] (%)	Corrections: Others[c] (mb)	Errors: Statistical (mb)	Errors: On beam contamination (mb)	Errors: Others (mb)	Total scattering cross section (mb)
			$\pi^- - p$ total scattering cross section			
373	35	0.95	0.9	0.9	0.5	28.9 ± 1.4
426	28	0.95	1.0	0.9	0.5	29.5 ± 1.4
468	25	1.00	0.64	0.9	0.5	30.0 ± 1.2
518	20	1.05	0.55	1.0	0.5	34.9 ± 1.3
567	18	1.14	1.27	1.3	0.5	44.6 ± 1.9
591	17	1.20	0.82	1.4	0.6	45.8 ± 1.7
604	16	1.25	1.15	1.4	0.6	45.5 ± 1.8
616	16	1.30	0.84	1.4	0.6	45.1 ± 1.7
643	15	1.36	1.57	1.3	0.7	44.4 ± 2.2
665	14	1.46	0.63	1.0	0.7	39.2 ± 1.4
719	12	1.70	0.86	0.9	0.8	35.1 ± 1.5
749	12	1.84	0.94	0.9	0.9	37.6 ± 1.6
769	10	1.90	1.48	0.9	0.9	37.4 ± 2.0
819	10	2.10	0.99	1.2	1.0	47.9 ± 1.9
840	9.5	2.20	1.17	1.4	1.1	54.6 ± 2.1
868	9.5	2.30	1.56	1.5	1.1	58.6 ± 2.4
890	9.5	2.37	1.26	1.4	1.2	57.8 ± 2.2
918	9.0	2.46	1.35	1.6	1.2	54.5 ± 2.4
943	9.0	2.60	1.72	1.5	1.3	50.4 ± 2.6
972	8.5	2.64	1.15	1.3	1.3	44.7 ± 2.2
1014	8.0	2.64	0.95	1.2	1.3	39.6 ± 2.0
1076	8.0	2.56	0.96	1.1	1.3	35.9 ± 2.0
1150	7.5	2.40	1.17	1.1	1.2	35.5 ± 2.0
			$\pi^+ - p$ total scattering cross section			
382	30.7	1.64	0.76	1.2	0.8	40.78 ± 1.62
476	20.5	1.25	0.56	0.7	0.6	23.67 ± 1.08
574	17.0	1.0	0.42	0.5	0.5	17.37 ± 0.82
633	13.0	0.9	0.40	0.45	0.4	15.16 ± 0.72
673	11.7	0.86	0.39	0.37	0.4	14.77 ± 0.67
778	9.3	0.92	0.39	0.49	0.5	19.44 ± 0.80
827	8.5	0.95	0.34	0.53	0.5	21.36 ± 0.81
847	8.2	0.95	0.34	0.57	0.5	22.42 ± 0.83
872	8.1	1.0	0.44	0.55	0.5	21.85 ± 0.86

[a]The uncertainty on the energy is $\pm 1\%$. The momentum spread of the beam is $\pm 1.8\%$.

[b]The contamination is the ratio $(\mu+e)/\pi$ of the total number of μ's and electrons in the beam to the number of π's.

[c]These include correction for elastic and inelastic scattering of particles into the last counter, and correction for scattering by air in the dummy target.

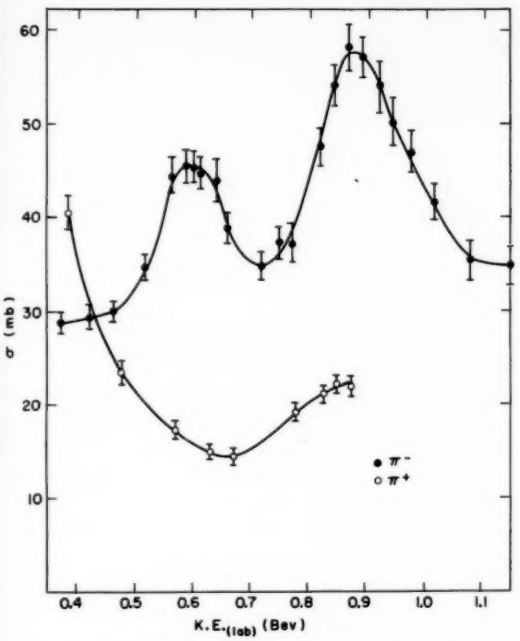

FIG. 1. Total π^--p and π^+-p scattering cross sections as a function of the π energy in the laboratory system.

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NEUTRAL BRANCHING RATIOS OF Λ AND K^0 PARTICLES*

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The neutral branching ratios of Λ and K^0 particles, defined by the relations

$$B_\Lambda \equiv \frac{w(\Lambda \to n + \pi^0)}{w(\Lambda \to n + \pi^0) + w(\Lambda \to p + \pi^-)},$$

$$B_K \equiv \frac{w(K_1^0 \to \pi^0 + \pi^0)}{w(K_1^0 \to \pi^0 + \pi^0) + w(K_1^0 \to \pi^+ + \pi^-)},$$

have already been investigated in hydrogen and propane bubble chamber experiments.[1-3] Because of the low gamma-ray detection efficiency of these devices, the statistically most significant results of these experiments have been based on comparisons of the numbers of associated ΛK_1^0, single Λ, and single K_1^0 decays via charged modes, rather than on direct detection of the neutral decay modes. On the other hand, the short radiation length of xenon makes it an ideal bubble chamber liquid for gamma-ray observation, and its use therefore permits the direct detection of the neutral decay modes with high efficiency.[4] We have taken 160 000 photographs in a 21-liter xenon bubble chamber exposed to a π^- beam of 1.0-1.1 Bev energy at the Berkeley Bevatron, for the purpose of making direct observations of the neutral decay modes. The results reported in this Letter are based on an analysis of about half of these pictures. Work on the rest of these data is now in progress.

Decay events with neutral secondaries were accepted in the samples used for the determination of B_Λ and B_K only if they contain two, three, or four electron pairs whose parent gammas originate at a common point inside the xenon. Furthermore, all charged and neutral Λ decays used in the measurement of B_Λ are associated with a K^0 decaying via its charged mode inside the chamber. Similarly all K^0 de-

cays used in the determination of B_K are associated with a Λ decaying via its charged mode in the chamber. With these requirements, we are sure of high scanning efficiency and unambiguous identification for the neutral decay modes. The expected energy and angular distributions of the gamma rays were computed from our observations of the charged decay modes, and were combined with the theoretical pair-production cross sections to obtain the conversion efficiencies. The results of this calculation were that the probability of converting both gammas from the neutral decay mode of the Λ is about 48%, whereas the chance of converting two, three, or all four gammas from the neutral decay mode of the K_1^0 is about 92% for the fiducial volume chosen.

After suitable correction for scanning efficiencies, we obtain the results

$$B_\Lambda = 0.33 \pm 0.07, \text{ based on 14 } \Lambda \to n + \pi^0 \text{ decays},$$

$$B_K = 0.25 \pm 0.05, \text{ based on 21 } K_1^0 \to \pi^0 + \pi^0 \text{ decays}.$$

The errors quoted are statistical standard deviations. These numbers may be compared with the predictions of the $\Delta I = 1/2$ selection rule, namely that $B_\Lambda = 1/3$ and $0.28 \leq B_K \leq 0.38$.[5] The predicted value of B_Λ is based on strict application of the $\Delta I = 1/2$ rule, whereas the prediction for B_K is based on the assumption of no $\Delta I = 5/2$ and enough admixture of $\Delta I = 3/2$ to account for the observed rate of the decay $K^+ \to \pi^+ + \pi^0$.[6] Our results are seen to agree satisfactorily with these predictions.

Further information can be obtained if we adopt an approach similar to that used in the analysis of hydrogen and propane bubble chamber experiments, confining ourselves for this purpose to the study of the charged decay modes. We can consider, for example, all interactions which have the following properties: (1) a K^0 is produced and decays via the mode $K_1^0 \to \pi^+ + \pi^-$; (2) no charged strange particle emerges from the interaction.[7] Under the assumption of strangeness conservation, there should also be a Λ emitted in each of these interactions, either directly[8] or as the decay product of a Σ^0. If we define R_Λ as the fraction of such interactions in which the decay $\Lambda \to p + \pi^-$ subsequently occurs, then the fraction in which the neutral mode $\Lambda \to n + \pi^0$ occurs will be given by $R_\Lambda B_\Lambda/(1 - B_\Lambda)$. We can now define

$$X_\Lambda \equiv 1 - \left[R_\Lambda + \frac{R_\Lambda B_\Lambda}{1 - B_\Lambda}\right]$$

as the fraction of such interactions that do not have an associated decay $\Lambda \to$ nucleon + pion.

After suitable correction for scanning efficiencies and Λ decays which occur outside the bubble chamber, we find

$$R_\Lambda = 0.58 \pm 0.06.$$

Combining this result with our value of B_Λ, we obtain

$$X_\Lambda = 0.13 \pm 0.07.$$

By a similar argument we can obtain values for the corresponding quantities R_K and X_K. For this purpose we select all interactions from which a $\Lambda \to p + \pi^-$ is emitted, and which also satisfy restriction (2) above. If we let R_K be the fraction of such interactions in which the decay $K_1^0 \to \pi^+ + \pi^-$ occurs, then the fraction in which the neutral mode $K_1^0 \to \pi^0 + \pi^0$ occurs will be given by $R_K B_K/(1 - B_K)$, and we can define

$$X_K \equiv 1 - \left[R_K + \frac{R_K B_K}{1 - B_K}\right]$$

Our results for R_K and X_K are

$$R_K = 0.40 \pm 0.04, \quad X_K = 0.47 \pm 0.04.$$

From these results we draw the following conclusions:

(*i*) The value of B_Λ is consistent with the $\Delta I = 1/2$ rule; the value of B_K is consistent with a $\Delta I = 1/2$ transition and a small admixture of $\Delta I = 3/2$.

(*ii*) Our value of X_K is in excellent agreement with the prediction of the particle mixture theory that the numbers of K_1^0 and K_2^0 are equal.

(*iii*) The small deviation of X_Λ from zero can probably be ascribed to the production of a small number of hyperfragments which would be undetected in our chamber. For this reason the difference between our value of R_Λ and that obtained by Crawford et al.[3] in a hydrogen bubble chamber, namely 0.63 ± 0.03, may in part be real. Indeed, if we combine our value of B_Λ and the Berkeley value of R_Λ, we obtain that 0.94 ± 0.11 of all Λ particles decay into a nucleon and pion.

We wish to express our gratitude to the staff of the Lawrence Radiation Laboratory for making this work possible, and especially to our many friends at the Bevatron who helped us very much during this experiment.

*Supported in part by the U. S. Atomic Energy Commission.

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[7]This requirement is imposed by restricting ourselves to those interactions from which all charged prongs stop without decaying inside the chamber.

[8]When we speak of a directly produced Λ, we mean that the hyperon which leaves the xenon nucleus in which the production takes place is a Λ. We make no distinction between a Λ which is actually the product of the initial pion-nucleon collision, and one which arises from the secondary interaction, in the same nucleus, of an initially produced Σ.

SEARCH FOR $\pi_{10}^0 \to 3\gamma$*

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The possible existence of a neutral meson of isotopic spin zero has been discussed in many connections.[1] The present note reports an experiment[2] to look for such a meson, using a method which covered only a small part of the possible mass spectrum, and which could detect the 3γ decay of a neutral meson of mechanical spin one, the π_{10}^0, but which could not detect the 2γ decay of the ordinary π^0. A small net effect of the form we sought was observed. However, because of the complexity of the expected background processes at such low cross sections, our experiment is not at all conclusive.

The experimental arrangement is shown in Fig. 1. The 160-Mev unpolarized external proton beam of the Harvard cyclotron falls on a 0.6-g/cm² target of ordinary lithium. A γ ray coming from the target is detected by one of three high-Z energy-sensitive Čerenkov counters. The Čerenkov liquid is $C_2H_2Br_4$, with a radiation length of 4.5 cm and an index of refraction such that protons of less than 210 Mev kinetic energy cannot give Čerenkov light directly. A counter consists of a $C_2H_2Br_4$ cylinder 13 cm long by 15 cm in diameter, viewed at each end by an RCA No. 7046 14-stage photomultiplier (shown on C_1 only) and placed with the counter axis normal to the direction from the target.

The threshold bombarding energy for production of ordinary π^0 mesons in the reaction $p + Li^7 \to Be^8 + \pi^0$ is 135 Mev. The maximum kinetic energy with which an ordinary π^0 can emerge at 120° in the laboratory is 21 Mev. The line from the

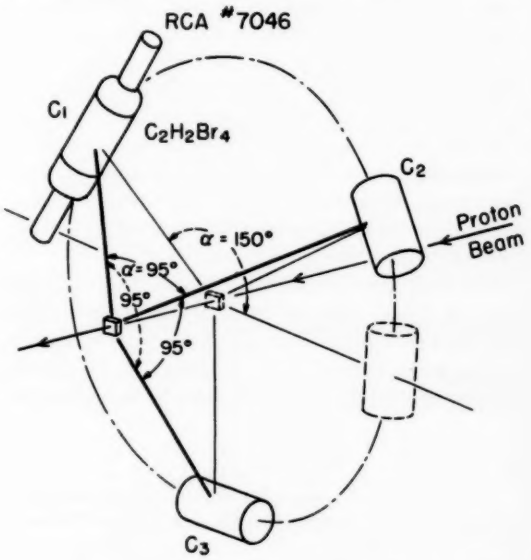

FIG. 1. Counter arrangement for twofold coincidence detection of γ rays from $\pi_{10}^0 \to 3\gamma$.

target to each counter makes an angle of 120° with the beam direction. With the counters set at the angles shown ($\alpha = 95°$ subtended by the center line of each pair of counters at the target), twofold coincidence detection of the two γ rays from the $\pi^0 \to 2\gamma$ decay by any part of the exposed area of the counters is forbidden kinematically.

On the other hand, two of the three γ rays from $\pi_{10}^0 \to 3\gamma$ can make a twofold coincidence in any of the three pairs of counters, provided such a π_{10}^0 can be produced at all. Note that the solid angle subtended by each counter (10^{-3} sterad) is such that no appreciable number of triple coincidences from $\pi_{10}^0 \to 3\gamma$ could be expected in this experiment. The purpose of having three counters instead of two is only to give a badly needed factor of three in intensity.

In addition to kinematic selectivity, the counters are biased so as to give appreciable energy selectivity. Their pulse-height responses were studied as a function of the energy of monoenergetic electrons produced by the MIT synchrotron. Their differential cosmic-ray pulse-height responses were used to monitor the biases during the run.

In order to run at high beam intensities, considerable effort was made to suppress the large neutron background. The mechanism by which neutrons could give counts with an efficiency of about 10^{-4} in the $C_2H_2Br_4$, and also in the lead glass counters used in preliminary runs, was not studied. The part of the background not associated with the target was reduced by shielding the detectors by 32 in. of lead and by replacing the air in the beam path with hydrogen. Crude absorption curves indicate that the residual target-associated singles at typical biases were about half neutrons and half γ rays. We estimate from the yields given below that π^0 decay accounts for most of the detected γ rays coming from the target.

To suppress accidental counts, fast coincidences (3×10^{-9} sec) between all four photomultipliers of each of the three possible pairs of counters were made in Berkeley circuits[3] set at low bias. To give energy discrimination, the pulses from each pair of photomultipliers on a given counter were then added, gated by the fast coincidence, and put through a Moody discriminator. The final coincidence outputs were formed by a redundant set of slower (20×10^{-9} sec) coincidence circuits. Delayed accidental coincidences between events from successive cyclotron pulses 42×10^{-9} sec apart were similarly processed and separately recorded in a parallel set of electronics. In order to remove systematic differences between the two sets, their roles were interchanged periodically between two modes of operation, called "*X*" and "*Y*."

First the excitation curve for ordinary $\pi^0 \to 2\gamma$ was measured with only one pair of counters; they were both at 90° to the beam axis and subtended an angle $\alpha = 150°$ at the target (see Fig. 1). The beam energy was varied by use of CH_2 absorbers, relying on the calculated ionization loss. The yield of π^0's from lithium as a function of proton energy is given in Fig. 2. The yields at $\alpha = 150°$ and a fixed energy $E_p = 160$ Mev are compared for a few different elements in Table I.

Then with the counters moved to the symmetric position shown in Fig. 1, with $\alpha = 95°$ for each of

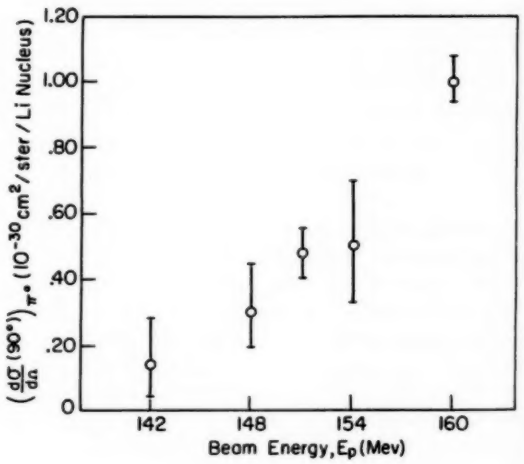

FIG. 2. Cross section for $p + Li^7 \to Be^8 + \pi^0$.

Table I. $[d\sigma(90°)/d\Omega]_{\pi^0}$ for several elements, in units of 10^{-30} cm^2 sterad^{-1} nucleus^{-1}.

Element	Li	C	Al	Cu	Pb
$[d\sigma(90°)/d\Omega]_{\pi^0}$	1.0 ± 0.1	0.3 ± 0.1	0.4 ± 0.1	0.3 ± 0.1	0.2 ± 0.1

Table II. Summary of coincidence data at $\alpha = 95°$.

Delay mode	Monitor counts[a]	Prompt coinc.	Delayed coinc.	Net[b]
	Beam energy = 160 Mev			
X	3900	55	32	23
Y	3250	45	22	23
Total	7150	100	54	46
	Beam energy = 133 Mev			
X	3900	30	37	-7
Y	2600	30	16	+14
Total	6500	60	53	7

[a]One monitor count = 4×10^9 protons.

[b]For comparison, the equivalent net ordinary π^0 coincidence counts ($\alpha = 150°$) at 160 Mev would be 2145 for 7150 monitor counts.

the three pairs of counters, the data given in Table II were obtained. The net rate observed at 160 Mev was $(2.0 \pm 0.6)\%$ of that from three pairs of counters counting ordinary π^0's in the $\alpha = 150°$ position.

Of the many types of background considered, only the following processes are expected to contribute appreciably to this net rate: (1) cosmic-ray coincidences, measured to give $(20 \pm 2)\%$ of the above net rate, (2) coincidences between one of the electrons and the gamma in the Dalitz pair decays, $\pi^0 \rightarrow e^+ + e^- + \gamma$, estimated to give $(10 \pm 3)\%$, and (3) coincidences between one of the γ rays from the π^0 and the nuclear γ ray in the reaction

$$p + \mathrm{Li}^7 \rightarrow \mathrm{Be}^{8*} + \pi^0 \rightarrow \mathrm{Be}^8 + \gamma(17\ \mathrm{Mev}) + 2\gamma,$$

estimated to give $(8 \pm 4)\%$.

The corrected net rate at $E_p = 160$ Mev, after subtracting these three backgrounds, is $(1.2 \pm 0.6)\%$ of the $\alpha = 150°$ ordinary π^0 equivalent counting rate. [At $E_p = 133$ Mev the net rate is $(-0.1 \pm 0.5)\%$.]

This rate would correspond to a differential cross section for production of the π_{10}^0 of $(d\sigma/d\Omega)_{\pi_{10}^0} = (1.6 \pm 0.8) \times 10^{-32}$ cm^2 sterad^{-1} (lithium nucleus)$^{-1}$, or $(2 \pm 1) \times 10^{-33}$ cm^2 sterad^{-1} nucleon^{-1}.

Akimov et al.[1] have in the meantime set an upper limit a factor of two lower than this for production of any neutral meson in another reaction $d + d \rightarrow \pi^0 + \mathrm{He}^4$, with considerably more energy available for the π^0 in the c.m. system.

In order to tell whether the net effect we observe is statistically and instrumentally well established, and in order to study the background processes in detail, we would have to work at a higher counting rate, requiring in turn considerable reduction of the target-associated background processes (2) and (3) above. This is very difficult to accomplish using a lithium target, but might be done by bombarding a hydrogen target with 350-Mev protons. Normal p-wave π^0 production is known to be suppressed by the parity and angular momentum selection rules, but there is no reason to believe that π_{10}^0 production would be suppressed. A collimated beam of 10^8 protons per seconds should suffice for a 2γ-detection counter experiment like this one. To provide sufficient solid angle for the conclusive detection of all three γ rays, the hydrogen target would need to be surrounded by a high-Z bubble chamber or electronic hodoscope.

We thank Professor Richard Wilson and other workers at the Harvard cyclotron for their kind hospitality and material help, and W. Beres, A. Buffington, P. Carr, G. Davidson, L. Hyman, A. Kuckes, D. Ritson, and M. Wahlig for much help in instrumentation and/or taking data. One of us (D.F.) is indebted to the Sloan Foundation for partial support in this research.

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‡Alfred P. Sloan Research Fellow.

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HIGH-ENERGY TOTAL CROSS SECTIONS FOR POSITIVE PIONS AND PROTONS ON HYDROGEN*

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(Received November 23, 1959)

On the basis of dispersion relations, Pomeranchuk has shown that if the (π^+,p) and (π^-,p) total cross sections approach constant values at high energies, these limits must be equal.[1] Considerable information is already available on the (π^-,p) total cross sections in the Bev range.[2-4] We present the results of an experiment at the Berkeley Bevatron in which (π^+,p) cross sections between 1.4 and 4.0 Bev/c were measured. Data on (p,p) total cross sections are also presented.

The experimental arrangement is shown in Fig. 1. Positive particles produced when the circulating proton beam strikes a target are bent inwards towards the center of the Bevatron by the magnetic field. In order to obtain positive pions with the highest possible momentum, the pion beam was brought out of the machine through a window on the inside radius. The beam is further deflected by bending magnets to keep it clear of the Bevatron structure and is focused by an 8-in.-bore doublet quadrupole.

Scintillation counters M_1, M_2, and M_3, each $1\frac{1}{2}$ in. in diameter, define the beam. Pions are distinguished from protons by requiring a coincidence with C, a gas Čerenkov counter[5] filled with sulfur hexafluoride to give an index of refraction of approximately 1.008. By putting C in anticoincidence with $M_1M_2M_3$, we obtained data on p-p scattering simultaneously with the (π^+,p) data.

After passing through the defining telescope, the beam impinged on a 4-ft-long liquid hydrogen target. The number of pions (and protons) transmitted was measured simultaneously at three different solid angles by means of counters S_1, S_2, and S_3. An extra coincidence in S_0 was added to reduce accidentals. The solid angles defined by S_1, S_2, and S_3 ranged from 0.6 to 4.3 millisteradians.

The coincidence circuits used were of the type described by Wenzel.[6] With the clipping lines employed, the resolving time was about 5×10^{-9} sec. The output of the monitor coincidence circuit was used as an input to a second circuit where a coincidence with S_0 and S_1 (for example) was required. Several species of accidentals were monitored throughout the experiments, and corrections to the data were made where necessary. Accidentals involving C were always less than 2% of the number of pions.

The momentum spread accepted by the counter telescope was approximately 2.5%, and the uncertainty in the momentum determination is estimated to be ±3%. Extensive magnetic shielding to reduce the Bevatron's leakage field was required along most of the beam line.

Data collection at each momentum involved series of runs with the H_2 target filled and empty; each series consisted of a full run preceded and followed by an empty run. The number of counts recorded in each series was usually sufficient to give a cross section with a statistical uncertainty of less than 1%. An analysis of the data from different measurements at the same momentum indicated that the probable error assigned to each measurement had to be increased to about 3%. The results given below are averages of two

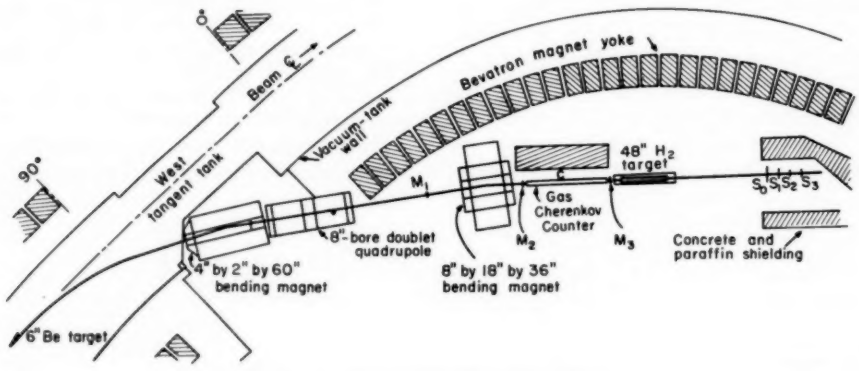

FIG. 1. Experimental arrangement.

or more measurements at each momentum. The uncertainty in the extrapolation to the zero solid angle subtended by the last counter was considered in assigning the errors. Where necessary, the data at the smaller solid angles were corrected for multiple Coulomb scattering by a method similar to that of Sternheimer.[7] These corrections were assigned a probable error of ±20% and had little effect on the extrapolated cross sections. Other possible sources of error are discussed below.

(A) Sources of error in the (π,p) measurements. A curve of the ratio of $M_1M_2CM_3$ counts to $M_1M_2M_3$ counts as a function of gas pressure in the Čerenkov counter indicated less than 2% electron contamination and less than 1% muon contamination at 1.8 Bev/c. Such a curve gives only the fraction of muons with momentum equal to or greater than that of the pions. The total muon contamination for the geometries and momenta used was determined by calculation, and corrections were made. The maximum was 2%. Practically all of the muons came from pions decaying after M_2, where the calculation is relatively simple.

(B) Sources of error in the (p,p) measurements. The errors assigned to the (p,p) cross sections have been increased to allow for the uncertainty in the efficiency of the anticoincidence circuits and the Čerenkov counter. If these were not 100% efficient in eliminating pion counts, the measured (p,p) cross sections would be low. The assigned errors are based on an efficiency between 90% and 100%.

K-meson contamination in the "proton beam" is estimated to be less than 1% for the momenta and take-off angles used in this experiment.

Table I. Total (π^+,p) and (p,p) cross sections.

Momentum (Bev/c)	$\sigma(\pi^+,p)$ (mb)	$\sigma(p,p)$ (mb)
1.40	39.4 ± 0.6	$46.9^{+1.0}_{-0.6}$
1.46	39.1 ± 0.8	$47.5^{+2.2}_{-1.1}$
1.60	35.8 ± 0.9	$47.7^{+3.0}_{-1.1}$
1.73	30.1 ± 0.5	$46.5^{+2.0}_{-0.6}$
1.89	28.4 ± 0.6	$46.3^{+3.2}_{-0.8}$
2.05	27.8 ± 0.6	$45.0^{+3.0}_{-1.0}$
2.47	29.0 ± 0.6	$45.6^{+1.9}_{-0.7}$
2.97	29.2 ± 0.5	$45.1^{+0.9}_{-0.5}$
3.58	29.2 ± 0.4	$43.3^{+0.6}_{-0.5}$
4.00	29.3 ± 0.4	42.4 ± 0.6

Our cross sections are shown in Table I and Fig. 2 which also shows data of other experimenters.[2,8,9] Our data for $\sigma(\pi^+,p)$ indicate a maximum near 1.5 Bev/c and an essentially constant cross section above 2.4 Bev/c. Our value at 4.0 Bev/c is 29.3 ± 0.4 mb. The best high-energy values for $\sigma(\pi^-,p)$ to date are 28.7 ± 2.6 mb at 4.3 Bev/c,[3] and 29.1 ± 2.9 mb at 5.2 Bev/c.[4]

We wish to acknowledge our indebtedness to Ken Lou for handling the many engineering problems encountered in the experiment, to Thomas Devlin for his help in conducting the experiment, and to the Bevatron staff and crew.

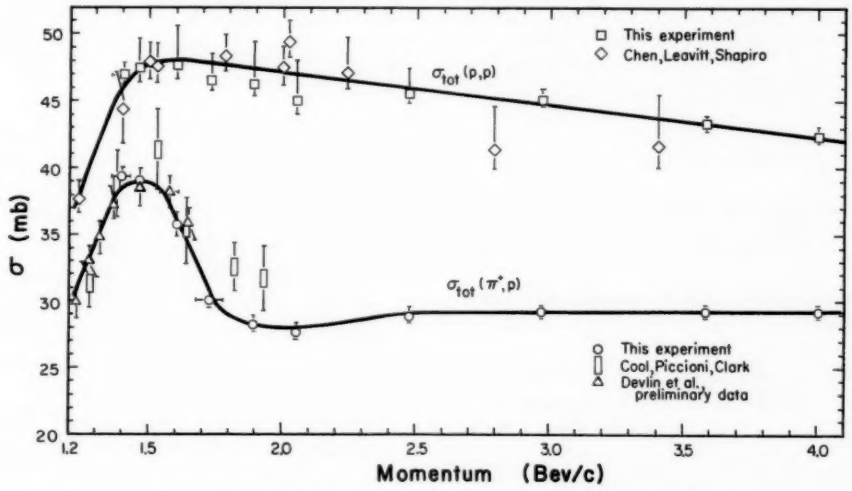

FIG. 2. Total (π^+,p) and (p,p) cross sections vs momentum.

*Work done under auspices of the U. S. Atomic Energy Commission.

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μ-MESON DECAY

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It was originally suggested by Yukawa[1] that the muon decay may be mediated by an unstable boson with weak couplings to lepton fields. More recently,[2,3] a charged, spin-one boson has been proposed in order to generate the V-A form of the weak decay interactions. It has already been pointed out[4] that a charged scalar intermediary can give rise to the desired couplings, providing an alternative but generally equivalent theory of the weak interactions. This applies when the first-order Kemmer formalism for spinless bosons is employed, but not with the use of the more conventional Klein-Gordon second-order theory.

The field equations in the Kemmer theory may be written

$$\varphi_\lambda = m^{-1}\partial_\lambda\varphi + m^{-2}(g_1^{(\mu)}J_\lambda^{(\mu)} + g_1^{(e)}J_\lambda^{(e)}),$$

$$\varphi = m^{-1}\partial_\lambda\varphi_\lambda + m^{-2}(g_2^{(\mu)}J^{(\mu)} + g_2^{(e)}J^{(e)}), \quad (1)$$

when both scalar and vector interactions are present, where

$$J_\lambda^{(e)} = \bar{\psi}_{(e)}\gamma_\lambda\frac{1-\gamma_5}{2}\psi_{(\nu)} + \text{c.c.},$$

$$J^{(e)} = \bar{\psi}_{(e)}\frac{1-\gamma_5}{2}\psi_{(\nu)} + \text{c.c.}$$

Only in the absence of any vector interaction is φ_μ simply proportional to $\partial_\mu\varphi$. The induced normal muon decay interaction, to lowest order in $g_1^{(e)}$ and $g_2^{(e)}$, is

$$m^{-2}g_1^{(\mu)}g_1^{(e)}\int d^4x\, J_\lambda^{(e)}(x)J_\lambda^{(\mu)}(x)$$

$$+\left(g_2^{(\mu)}+g_1^{(\mu)}\frac{m^{(\mu)}}{m}\right)\left(g_2^{(e)}+g_1^{(e)}\frac{m^{(e)}}{m}\right)$$

$$\times\int d^4x\, d^4x'\, J^{(e)}(x)\,D_F(x-x',m)\,J^{(\mu)}(x'). \quad (2)$$

The first term is a purely local V-A interaction, the second a nonlocal S-P interaction. If $g_2^{(e)} = 0$, the scalar admixture for muon decay becomes $m^{(\mu)}m^{(e)}/m^2$ – less than 10^{-4} for nucleonic mass of the intermediary.[5] Alternatively, if either or both of the factors $[g_2^{(\mu)} + g_1^{(\mu)}(m^{(\mu)}/m)]$ and $[g_2^{(e)} + g_1^{(e)}(m^{(e)}/m)]$ are set equal to zero, the normal μ-decay interaction (to this order in g) becomes a purely local one.

Using the Klein-Gordon formalism, we obtain

a muon decay interaction identical to Eq. (2) except for the absence of the direct vector coupling. The two versions of the spin-zero theory are identical for $g_1^{(e)}=0$, and in general differ only by a direct self-interaction of $J_\lambda^{(e)}$. The choice between these formalisms depends upon whether one regards first-order or second-order field equations as the more basic. [It is only the Kemmer theory that may be developed according to the canonical formulation of Schwinger.[6]]

For the discussion of $\mu\to e+\gamma$, we shall assume $g_2^{(e)}=0$ and neglect finite contributions proportional to the electron mass. The matrix element for this mode becomes (q = photon momentum)

$$\frac{e}{96\pi^2}\frac{g_1^{(\mu)}g_1^{(e)}}{m^2}\bar{\psi}_{(e)}\frac{1-\gamma_5}{2}\left\{\tfrac{1}{2}m^{(\mu)}\sigma_{\alpha\beta}F^{\alpha\beta}-\gamma_\mu A_\mu q^2\left[\ln\left(\frac{K^2}{m^2}\right)+c+O\left(\frac{q^2}{m^2}\right)\right]\right\}\psi_{(\mu)},$$

where K is a cutoff to the divergent momentum integration, and c is a finite constant which depends upon the manner in which the cutoff is introduced. The decay interaction contains a finite, point-like, "moment" interaction, and a divergent "charge" interaction which does not contribute to the free-particle decay. The branching ratio for the decay of a free muon into the $e+\gamma$ channel is

$$\rho=\alpha/24\pi\approx 10^{-4},$$

which is ~40 times greater than the current experimental upper limit.[7] In contrast to the result with a vector intermediary,[8-10] the result is both convergent and unambiguous.

We should like to thank Professor C. J. Bakker and Professor M. Fierz for the hospitality extended to us at CERN.

*National Science Foundation Post-Doctoral Fellow.
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SOME GRAVITATIONAL WAVES*

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The few hitherto known wave-like exact solutions of the Einstein gravitational equations represented either plane[1,2] or cylindrical[3] waves. We here intend to derive a new class of solutions, displaying a lesser degree of symmetry, and thus more generality.

Let us consider the metric

$$ds^2=-dx^2-dy^2-dz^2+dt^2-2f(x,y,z+t)(dz+dt)^2.$$

One can easily show that $R_{zz}=R_{zt}=R_{tt}=f_{xx}+f_{yy}$, and other components vanish. If f is a harmonic function of x and y, this metric thus satisfies Einstein's equations in vacuo, whatever may be its dependence on $(z+t)$.

A convenient tetrad of orthonormal vectors is

$$h_{(1)}^{\ k}=(\cos a,\ \sin a,\ 0,\ 0),$$
$$h_{(2)}^{\ k}=(-\sin a,\ \cos a,\ 0,\ 0),$$
$$h_{(3)}^{\ k}=(0,\ 0,\ 1-f,\ f),$$
$$h_{(4)}^{\ k}=(0,\ 0,\ -f,\ 1+f),$$

where $\tan(2a)=(f_{xy}/f_{xx})$. The only nonvanishing independent physical components[4] of the curvature tensor are

$$\sigma=R_{(m1n1)}=-R_{(m2n2)}=(f_{xx}^{\ 2}+f_{xy}^{\ 2})^{1/2},$$

where m and n take the values 3 and 4 only. Our

metric thus belongs to the second class of Petrov's classification.[4]

Let us examine two examples. If

$$f = (x^2 - y^2)\sin(z + t),$$

one has $\sigma = 2\sin(z + t)$. This is a plane monochromatic wave.

Another example is

$$f = xy(x^2 + y^2)^{-2}\exp[b^2 - (z + t)^2]^{-2} \text{ for } |z + t| < b,$$

$$f = 0 \text{ for } |z + t| \geq b.$$

(Note that f has derivatives of all orders at $|z + t| = b$.) This is a wave packet travelling with unit velocity in the negative z direction. It contains the singular segment $x = y = 0$, $-b - t < z < b - t$. The question of the existence of stable regular gravitational wave packets is still open.

If $f_{xx} + f_{yy} \neq 0$, one still has $g^{mn}R_{mn} = 0$ and $g^{mn}R_{mr}R_{ns} = 0$. The source of f can then be interpreted as a null electromagnetic field.[5]

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*Partly supported by the U. S. Air Force, through the Air Research and Development Command.

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ERRATUM

MULTIPLE COULOMB EXCITATION IN Th^{232} AND U^{238}. F. S. Stephens, Jr., R. M. Diamond, and I. Perlman [Phys. Rev. Letters 3, 435 (1959)].

In Fig. 2(b) the transition energy between the 10+ and 8+ levels of Th^{232} should read 273 kev instead of 373 kev.

ABSTRACTS

In this section are printed the abstracts of Articles that have been forwarded to The American Institute of Physics for publication in THE PHYSICAL REVIEW. In quoting information obtained from this section before the appearance of the corresponding Article, reference should be made to "Physical Review (to be published)" rather than to this Journal.

DIFFRACTION OF THERMAL WAVES IN LIQUID HELIUM II BY A SPHERICAL MIRROR. J. Fajans, Stevens Institute of Technology, Department of Physics, Hoboken, New Jersey (Received May 28, 1959).

Diffraction patterns of 3- and 13-kc/sec thermal waves in liquid helium II caused by a spherical mirror were measured. The main features of the patterns were developed from the Kirchhoff diffraction formula combined with a standing-wave distribution. Both the amplitude and phase of the wave at each point of space could be determined.

EXCLUSION FACTORS IN TRANSPORT THEORY. E. I. Blount, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania (Received July 29, 1959).

It has recently been shown that the customary exclusion factors should be omitted from the Boltzmann equation. This raises some conceptional difficulties in relation to the Pauli principle. The resolution of these difficulties is discussed in this paper.

MANY-BODY PROBLEM IN QUANTUM STATISTICAL MECHANICS. V. DEGENERATE PHASE IN BOSE-EINSTEIN CONDENSATION. T. D. Lee, Columbia University, New York, New York, and C. N. Yang, Institute for Advanced Study, Princeton, New Jersey (Received July 31, 1959).

The formulation of the previous paper (paper IV) is extended so that it becomes applicable in an interacting system in the presence of a Bose-Einstein degeneracy. This extension is carried out by the introduction of an x-ensemble, which enables one to utilize an Ursell type expansion even in the presence of a Bose-Einstein degeneracy. The variational principle of the previous paper is also extended. It is proved that in the presence of a Bose-Einstein degeneracy, the average occupation number of a single particle state with momentum $\vec{p}$ approaches infinity as $\vec{p} \to 0$. The method is applied to a dilute system of Bose hard spheres.

ELECTRON AND ION RUNAWAY IN A FULLY IONIZED GAS. II. H. Dreicer, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico (Received July 17, 1959).

The treatment presented in an earlier paper is extended to give a more exact estimate of the particle runaway rate in a fully ionized gas under the action of a weak applied electric field. By analyzing the motion of particles in various regions of velocity space, it is shown that in any weak applied electric field some particles will always run away. The rate at which this occurs is determined by the flow of particles from the collision-dominated to the electric-field-dominated region of velocity space. The probability, $Q(\tau)$, of electron runaway as a function of time is calculated with the help of the Boltzmann-Fokker-Planck equation and can be expressed in the form $Q(\tau) = 1 - \exp(-\lambda_1 \tau)$. The runaway rate, λ_1, is presented as a function of applied electric field, and the plasma temperature and density. It exceeds by several orders of magnitude the rate recently proposed by Harrison. The runaway rate for positive ions is shown to be exceedingly small compared to λ_1, in the circumstances usually encountered.

A brief discussion is devoted to the experimental evidence, the effects of magnetic fields, and the excitation of plasma instabilities. The correction which particle runaway introduces in the equation of pressure balance is presented for the case of a static pinched discharge.

ELECTRON VELOCITY DISTRIBUTIONS IN A PARTIALLY IONIZED GAS. H. Dreicer, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico (Received July 17, 1959).

The Boltzmann method is applied to the problem of calculating the electron velocity distribution in a partially ionized gas. Inelastic collisions with neutral molecules as well as random two-body Coulomb interactions are included.

The latter are treated by use of the Fokker-Planck equation. Application is made to a hydrogen plasma subjected to an externally applied electric field. Static solutions are obtained, by numerical means, as a function of the ionization degree, and the classical gas discharge parameter, E/p. It is shown that the evolution of the electron velocity distribution function from that characteristic of a poorly ionized gas to the Maxwellian distribution occurs over a very large range in ionization degree. Several applications are also made to energy relaxation phenomena, and the electrical conductivity is evaluated.

He II FILM PROFILE AND RELATIVE IMPORTANCE OF HEIGHT AND SURFACE PRESSURE. O. T. Anderson,* D. H. Liebenberg, and J. R. Dillinger, University of Wisconsin, Madison, Wisconsin (Received July 29, 1959).

The thickness d of the He II film at 1.40°K vs height h to 40 cm has been measured by an optical method. Results agree better with an expression of the form $d = kh^{-1/3}$ than with $d = kh^{-1/2}$ or $h = (a/d)^3 + (b/d)^2$. Evidence was obtained suggesting that the contour of the film cannot be accounted for by considering it to be an adsorbed film subjected to a varying pressure. The pressure would decrease with height due to gravitational effects in a vertical gas column.

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HEAT TRANSPORT IN LIQUID He^3. D. M. Lee* and Henry A. Fairbank, Physics Department, Yale University, New Haven, Connecticut (Received July 20, 1959).

The thermal conductivity of liquid He^3 at a pressure of 2/3 atmosphere has been determined experimentally and found to increase slowly from 7×10^{-5} watt/cm °K at 0.24°K to 16×10^{-5} watt/cm °K at 2.7°K with no evidence of superfluidity. Several models of liquid He^3 based on Fermi-Dirac statistics predict a $1/T$ dependence for the thermal conductivity of He^3 at the lowest temperatures, but no such behavior has been observed down to 0.24°K in the present work. A study of the convective heat transport in the liquid has indicated that the coefficient of thermal expansion becomes negative below about 0.5°K. A thermal boundary resistance across a copper–liquid-He^3 interface has been found which is similar in magnitude and temperature dependence to that found for a copper–superfluid-He^4 boundary.

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IONS IN LIQUID HELIUM. K. R. Atkins, Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania (Received July 16, 1959; revised manuscript received September 30, 1959).

The mobility of an ion in liquid He^4 is known to be appreciably less than the mobility of a He^3 atom and varies in a different way with temperature. It is suggested that the essential difference is that electrostriction effects increase the liquid density over a large region surrounding the ion, so that the ion drags around with it about 50 He^4 atoms. The density field of the positive ion is calculated in a semiclassical approximation. A possible difference between the density fields for positive and negative ions is briefly discussed. Various experimental ways of checking this picture of an ion are suggested.

HEXAGONAL FERRIMAGNETIC COMPOUND CONTAINING FLUORINE. E. H. Frei, M. Schieber, and S. Shtrikman, Department of Electronics, The Weizmann Institute of Science, Rehovot, Israel (Received July 20, 1959).

A partial substitution of the oxygen ions by fluorine in $BaO\cdot 6Fe_2O_3$ is reported. The new compound with a formula near to $BaF_2\cdot 2FeO\cdot 5Fe_2O_3$ has at room temperature a magnetization saturation of 72 cgs units/gram compared to 67 cgs units/gram for $BaO\cdot 6Fe_2O_3$. The specific gravity, Curie temperature, and unit-cell dimensions are practically the same for both compounds.

EFFECTS OF POLARIZED LIGHT ON PHOTOCURRENTS AND PHOTOVOLTAGES IN ZnS. G. Cheroff, R. C. Enck, and S. P. Keller, Research Laboratory, International Business Machines Corporation, Poughkeepsie, New York (Received July 16, 1959).

The anomalous short-circuit photocurrents in ZnS have been measured using polarized light. In spite of the fact that for a given wavelength,

light polarized perpendicular to the c axis is more strongly absorbed than light polarized parallel to the c axis, there are wavelength regions in which the absolute magnitude of the short-circuit photocurrents is smaller for perpendicularly polarized light. The data are consistent with a double valence band model.

X-RAY-INDUCED ELECTRICAL POLARIZATION IN GLASS. T. M. Proctor,* Research and Development Division, Corning Glass Works, Corning, New York (Received June 22, 1959).

Electrical polarization in a lead silicate glass induced by the action of x-rays on the material is found to exist. This phenomenon is surveyed experimentally as a function of total dose (incident and absorbed), dose rate, x-ray tube potential, radiation temperature, and temperature at which the polarization is released and measured. Net surface charges of the order of 10^{-9} coulomb/cm^2 can be obtained from 3-mm thick samples irradiated at room temperature with 10^5 r of 250-kv x-rays. To the first order the buildup and decay of this condition seems to follow the normal electrical relaxation as can be theoretically predicted from the dielectric and resistivity constants of the material ($\tau = \rho\epsilon$). Measured surface charge is shown to be proportional to absorbed dose for smaller doses; however, for greater doses final equilibrium in the polarization is reached when back electrical conduction becomes as large as the forward x-ray-induced displacement current. The dependence of measured surface charge upon the sample thickness has been experimentally investigated for one case.

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SUPERPARAMAGNETISM, NONRANDOMNESS, AND IRRADIATION EFFECTS IN Cu-Ni ALLOYS. F. M. Ryan,* E. W. Pugh,† and R. Smoluchowski, Carnegie Institute of Technology, Pittsburgh, Pennsylvania (Received July 6, 1959).

The effect of neutron irradiation on copper-nickel alloys has been investigated by means of magnetic susceptibility measurements. The susceptibilities were measured by the Gouy method between 300°K and 2.0°K for a series of alloys ranging from 17.22 to 46.5 atomic percent nickel. It is shown that without superparamagnetism an unreasonable magnetic moment per nickel atom has to be assumed. This model is confirmed by irradiation studies in which samples were exposed to neutron fluxes at the Brookhaven reactor, ranging up to 2.2×10^{19} neutrons/cm^2 while at 80°C, and the magnetic susceptibilities were found to increase following the irradiation. The increase was easily observable due to its strong temperature dependence, and was greatest for the samples with the highest nickel content and for samples exposed to the highest neutron fluxes. The susceptibilities of the alloys returned to their original values following an anneal in or above the temperature range where self-diffusion becomes important, while no changes in the susceptibilities were observed following anneals at lower temperatures. It is suggested that the copper-nickel system is not a perfect random solid solution but tends toward segregation, and that the neutron irradiation enhances diffusion toward a true equilibrium at room temperature. This is in agreement with several other observations.

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INTERPRETATION OF MAGNETIC PROPERTIES OF DYSPROSIUM. S. H. Liu, D. R. Behrendt,* S. Legvold, and R. H. Good, Jr., Institute for Atomic Research and Department of Physics, Iowa State University, Ames, Iowa (Received June 11, 1959; revised manuscript received August 28, 1959).

Dysprosium is ferromagnetic below 85°K, antiferromagnetic between 85 and 179°K, and paramagnetic above 179°K. The spontaneous magnetic moment lies always in the basal plane, and there is anisotropy in this plane below 110°K. In the present paper it is shown that the magnetic properties can be interpreted in terms of a two-sublattice model and a phenomenological theory similar to a theory proposed by Néel. Detailed agreement for the magnetization curves in the ferromagnetic and antiferromagnetic regions is obtained.

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THEORY OF SPIN-WAVE INTERACTIONS IN FERRO- AND ANTIFERROMAGNETISM. Takehiko Oguchi,* Sarah Mellon Scaife Radiation Laboratory, University of Pittsburgh, Pittsburgh, Pennsylvania (Received July 17, 1959).

The spin-wave theory in an ideal Heisenberg model of a ferromagnet is studied using Holstein and Primakoff's method including the spin-wave interactions. Several earlier published results of the correction to the spontaneous magnetization produced by spin-wave interactions were in disagreement with each other, and they were not in agreement with Dyson's result which is regarded as rigorous at low temperatures. Our result is in agreement with Dyson's to the order which we have considered.

Our method can be applied to antiferromagnetism easily. We have obtained the correction arising from interactions between spin waves. The correction term is quite small. This means that the simple theory neglecting the spin-wave interactions is sufficient for practical purposes.

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ELECTRON CAPTURE OF LATTICE VACANCY IN Si. Akira Morita,* Department of Physics, Purdue University, Lafayette, Indiana (Received July 17, 1959).

The electron-capture cross section of the deep trap due to a lattice vacancy in Si is calculated by taking into account the distortion of the lattice vibrations by the lattice vacancy. It is assumed that the trap is a neutral center for electron capture. The results show that although the distortion effect enlarges the calculated cross section by three orders of magnitude at 300°K, it is not enough to explain the magnitudes of observed cross sections.

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LINEAR ANTIFERROMAGNETIC CHAIN. Sergio Rodriguez,* Scientific Laboratory, Ford Motor Company, Dearborn, Michigan (Received July 22, 1959).

It is shown that a linear chain consisting of a large number of atoms of spin $\frac{1}{2}$ with nearest neighbor ferromagnetic or antiferromagnetic interactions is mathematically equivalent to a one-dimensional Fermi gas with two-body forces. This equivalence is used to construct a wave function for which the expectation value of the energy lies between the two approximations obtained by Hulthén. Also, a perturbation treatment is given which permits one, in principle, to obtain the exact antiferromagnetic ground state.

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INTERACTION OF DISLOCATIONS WITH AN APPLIED STRESS IN ANISOTROPIC CRYSTALS. G. deWit and J. S. Koehler, University of Illinois, Urbana, Illinois (Received July 16, 1959).

The equilibrium shape of a dislocation segment between two pinning points in the same glide plane is calculated. The assumption is made that the dependence of the dislocation self energy on the geometry of the dislocation line can be expressed by using an energy per unit length, E, which is a function only of the angle, θ, between the Burgers vector and the tangent to the dislocation. Only glide of the dislocation, not climb, is considered. The results obtained are compared with those for elastically isotropic crystals. It is found that the character of the dislocation shape is altered considerably if $E+d^2E/d\theta^2$ can be negative. It is suggested that the change in sign of this quantity is associated with diffusionless phase changes.

INFLUENCE OF ELASTIC ANISOTROPY ON THE DISLOCATION CONTRIBUTION TO THE ELASTIC CONSTANTS. J. S. Koehler and G. deWit, University of Illinois, Urbana, Illinois (Received July 16, 1959).

Calculations of the dislocation contribution to the measured elastic constants of face-centered cubic crystals are made as follows. First, the displacement of a pinned dislocation segment under an externally applied stress is evaluated. Then the contribution to the resulting macroscopic distortion of the specimen resulting from the motion of all the dislocations present is calculated. The results are that the contributions for given dislocation arrangement increase with increasing anisotropy. For copper and lead the contributions can amount to a few percent in a pure well-annealed crystal and can be as large as 10% in

slightly deformed crystals. Edge dislocations are found to make about ten times larger contributions than a similar density of screw dislocations.

QUASI-PARTICLES AND GAUGE INVARIANCE IN THE THEORY OF SUPERCONDUCTIVITY. Yoichiro Nambu, The Enrico Fermi Institute for Nuclear Studies and the Department of Physics, The University of Chicago, Chicago, Illinois (Received July 23, 1959).

Ideas and techniques known in quantum electrodynamics have been applied to the Bardeen-Cooper-Schrieffer theory of superconductivity. In an approximation which corresponds to a generalization of the Hartree-Fock fields, one can write down an integral equation defining the self-energy of an electron in an electron gas with phonon and Coulomb interaction. The form of the equation implies the existence of a particular solution which does not follow from perturbation theory, and which leads to the energy gap equation and the quasi-particle picture analogous to Bogoliubov's.

The gauge invariance, to the first order in the external electromagnetic field, can be maintained in the quasi-particle picture by taking into account a certain class of corrections to the charge-current operator due to the phonon and Coulomb interaction. In fact, generalized forms of the Ward identity are obtained between certain vertex parts and the self-energy. The Meissner effect calculation is thus rendered strictly gauge invariant, but essentially keeping the BCS result unaltered for transverse fields.

It is shown also that the integral equation for the vertex parts allows homogeneous solutions which describe collective excitations of quasi-particle pairs, and the nature and effects of such collective states are discussed.

MEASUREMENTS OF EQUILIBRIUM VACANCY CONCENTRATIONS IN ALUMINUM. R. O. Simmons and R. W. Balluffi, University of Illinois, Urbana, Illinois (Received July 31, 1959).

Measurements of change in length and change in lattice parameter were made at identical temperatures on 99.995% aluminum in the temperature range 229 to 656°C. Length changes, ΔL, were measured on an unconstrained horizontal bar sample using a rigid pair of filar micrometer microscopes. X-ray lattice parameter changes, Δa, were observed using a high-angle, back-reflection, rotating-single-crystal technique. The measurements are compared to earlier work. The relative expansions $\Delta L/L$ and $\Delta a/a$ were equal within about $1:10^5$ from 229 to 415°C. At higher temperatures additional atomic sites were found to be generated; the difference between the two expansions could be represented by $3(\Delta L/L - \Delta a/a) = \exp(2.4)\exp(-0.76\ \text{ev}/kT)$. At the melting point (660°C) the equilibrium concentration of additional sites is $3(\Delta L/L - \Delta a/a) = 9.4\times10^{-4}$. This result is independent of the detailed nature of the defects, for example, the lattice relaxation or degree of association. The nature of the defects is considered and it is concluded that they are predominantly lattice vacancies; it is estimated that the divacancy contribution at the melting point may well be less than about 15%, corresponding to a divacancy binding energy ≤ 0.25 ev. The observed formation energy agrees with the values obtained by quenching techniques and by interpretation of the high-temperature electrical resistivity of identical material by Simmons and Balluffi. The present work is the first direct measurement of formation entropy; the value is near that expected from theoretical considerations. The contributions of the thermally generated defects to other physical properties at high temperatures is considered briefly.

MEASUREMENTS OF THE HIGH-TEMPERATURE ELECTRICAL RESISTANCE OF ALUMINUM: THE RESISTIVITY OF LATTICE VACANCIES. R. O. Simmons and R. W. Balluffi, University of Illinois, Urbana, Illinois (Received July 31, 1959).

The electrical resistance of a 99.995% aluminum wire was measured at temperatures from 14 to 655°C. Values of temperature coefficient of resistance and of resistivity are derived; they differ somewhat from earlier work. The resistivity values show a progressive increase above the expected values at high temperatures; this is ascribed to scattering by thermally-generated point defects of the type which add atomic sites (vacancy-type defects), whose equilibrium concentrations have been measured directly in identical material at identical temperatures by Simmons and Balluffi. Three different semiempirical methods were used to estimate the expected values of the ideal lattice resistivity in the ab-

sence of defects; they gave similar results. The limitations of extrapolation methods are discussed. The resistivity increment ascribed to the vacancy-type defects was then obtained by difference and can be represented by $\Delta\rho = (4.4 \times 10^{-3}$ ohm-cm)$\exp(-0.77\,\text{ev}/kT)$. The observed formation energy is in close agreement with that obtained by direct concentration measurements and with that obtained in various quenching investigations. This increment is nearly twice the value expected from extrapolation of recent quenching work from the interval 260° to 320°C, however. This relatively small discrepancy can be ascribed to three factors, whose relative importance cannot be precisely evaluated at present. They are (1) failure of quenching techniques to retain all of the equilibrium defect concentrations, (2) the presence of appreciable divacancy concentrations at the highest temperatures, and (3) a contribution to the high-temperature resistivity arising from lattice anharmonicity. The increment of about 0.30 μohm-cm at the melting point (660°C) corresponds to a resistivity 3 μohm-cm/atom percent monovacancies, in agreement with a crude estimate based upon known effects of solute atoms of different valence.

CORRELATION ENERGY IN A MODEL SEMICONDUCTOR. J. Callaway, Department of Mathematics, Queen Mary College, University of London, London, England (Received July 27, 1959).

The correlation energy of the electrons in a semiconductor is expected to be less than in a metal with the same electron density. The reduction occurs because the existence of an energy gap between filled and empty states tends to increase the magnitude of the energy denominators of perturbation theory. This effect is studied in a simple model, based on the calculations of Gell-Mann and Brueckner, in which the semiconductor is represented as a free electron gas with an energy gap above the Fermi surface. The correlation energy then depends on the ratio of the energy gap to the valence bandwidth as well as on the density. It is shown that for an energy gap large compared to the bandwidth, second order perturbation theory is correct; while for a small energy gap, an explicit correction to the Gell-Mann–Brueckner series can be obtained.

CALCULATION OF THE COHESIVE ENERGY OF METALLIC IRON. Frank Stern, United States Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland (Received July 20, 1959).

The cohesive energy of metallic iron is calculated for the body-centered cubic structure in a singlet spin state at 0°K. The potential field acting on each electron is taken to be that of the ion core and of the remaining valence electrons in the same lattice cell; thus the calculation becomes equivalent to one for the free atom as the lattice constant is increased. Tight-binding wave functions are used, but they are modified by expanding the contributions from neighboring atoms in a power series within a cell, and orthogonalizing to core states. Evaluating the complete wave function in each cell eliminates the need for multi-center integrals otherwise required in the tight-binding method. The wave functions for wave vectors in directions of high symmetry have a rather simple form, and can be described by a few parameters. States near the bottom of the $3d$ band tend to have a more diffuse charge distribution than do the states near the top of the band. Thus the x-ray scattering factor per electron for a partially filled $3d$ band will be less than that for a full band. Calculations of the energy of the solid are made for three values of the atomic sphere radius, r_s, using atomic wave functions from the $3d^7 4s$ configuration. The indicated configuration in the solid is close to $3d^7 4s$, making the calculation approximately self-consistent. The calculated width of the occupied portion of the $3d$ band is 0.33 ry. We find the cohesive energy of metallic iron to be 0.43 ± 0.2 ry per atom, which is consistent with the experimental value, 0.32 ry. The equilibrium lattice constant and the compressibility are both found to be in good agreement with experiment. An attempt to replace the Coulomb hole used in the main calculation by an exchange hole, using a single Slater determinant wave function, gave far too little binding.

SATURATION MAGNETIZATION OF NICKEL FILMS OF THICKNESS LESS THAN 100 A. C. A. Neugebauer, General Electric Research Laboratory, Schenectady, New York (Received July 29, 1959).

Nickel films varying in thickness from 200 to 3 A were prepared by evaporation on glass sub-

strates in a vacuum sufficiently high to prevent gas adsorption on the film during preparation and measurement. Their magnetization was measured as a function of field up to 10 000 oe using a vacuum torsion magnetometer. The saturation magnetization of these films was determined as a function of their thickness at 300°K and 77°K. No decrease in saturation magnetization from that of bulk nickel has been observed for films of thickness down to 20 A, at room temperature. The Curie temperature of a 27A film was found to coincide with that of bulk nickel. The magnetic behavior of films in the thickness range below 20 A suggests superparamagnetism rather than a decrease in the saturation magnetization. Measurements of the magnetostrictive anisotropy constant indicate that the films as originally prepared are in a state of high tensile strain, which can be relieved by annealing. The thin-film nature of some specimens was ascertained by examination in the electron microscope.

TEMPERATURE DEPENDENCE OF THE MAGNETIZATION OF DYSPROSIUM METAL. Kazuo Niira,* Institute for Atomic Research and Department of Physics, Iowa State University of Science and Technology, Ames, Iowa (Received July 23, 1959).

In this paper the experimental fact that the temperature dependence of the saturation magnetic moment of dysprosium metal shows a marked departure from the Bloch $T^{3/2}$ law at low temperatures is interpreted as due to magnetic anisotropy. The calculation is in the spin wave approximation and gives a result which agrees well with the observed temperature dependence of the magnetization if the magnitude of the magnetic anisotropy is suitably chosen. A discussion on the atomic origin of the magnetic anisotropy is given.

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ELECTRON SPIN-LATTICE RELAXATION IN PHOSPHORUS-DOPED SILICON. A. Honig and E. Stupp, Syracuse University, Syracuse, New York (Received July 23, 1959).

Electron spin-lattice relaxation in phosphorus-doped silicon has been investigated over a magnetic field range of 0 to 11 000 oersteds, a temperature range of 1.25°K to 4.2°K, and a concentration range of 10^{14} P/cc to 3×10^{16} P/cc. Three distinct τ_S ($\Delta m_S = \pm 1$, $\Delta m_I = 0$) relaxation mechanisms have been identified, and their functional dependences on magnetic field, temperature and concentration have been determined. These mechanisms are characterized as follows: (a) $1/\tau_S[H^4, T]$ is concentration independent, and has an H^4 and T dependence. At 3000 oersteds and 1.25°K, $1/\tau_S[H^4, T] = (2.63 \pm 0.10)\times10^{-5}$ sec^{-1}. (b) $1/\tau_S[T^7]$ is independent of concentration and magnetic field, and has a T^7 dependence. At 2.00°K, $1/\tau_S[T^7] = (1.65 \pm 0.15)\times10^{-4}$ sec^{-1}. (c) $1/\tau_S$[conc.] depends linearly on concentration for concentrations below 10^{16} P/cc, and has approximately an $H^{-1/2}$ and T dependence. At 3000 oersteds and 1.25°K, $1/\tau_S$[conc.] for a 4×10^{15}-P/cc sample is $(3.3 \pm 0.4)\times10^{-4}$ sec^{-1}. In addition to these three τ_S mechanisms, the horizontal relaxation modes ($\Delta m_I = \pm 1$, $\Delta m_S = 0, \pm 1, \mp 1$) were investigated. $1/\tau_X(\Delta m_I = \pm 1, \Delta m_S = \mp 1)$ at 2.16°K is independent of concentration and magnetic field, and between 2.16°K and 4.2°K, has a $T^{6.5}$ temperature dependence; all of which strongly suggests a dominant Raman process in this temperature region. At 2.16°K, $\tau_X = 3.0 \pm 0.4$ hours. At 1.25°K, the magnetic field dependence of the horizontal modes was measured. The large errors (associated with the very long items involved) make it difficult to ascertain the dominant mechanism here. However, our results are not consistent with a quadratic magnetic field dependence of $1/\tau_X$. At low magnetic fields, concentration-dependent $\tau_N(\Delta m_I = \pm 1, \Delta m_S = 0)$ and τ_X mechanisms arise, due to an admixture of states which allows $1/\tau_S$[conc.] also to induce $1/\tau_N$ and $1/\tau_X$ transitions. When all the preceding mechanisms are properly superposed, their resultant agrees well with the experimental relaxation probabilities, except for a small discrepancy which shows up for dilute samples at 1.25°K. This discrepancy ($\sim 2\times10^{-5}$ sec^{-1} at 1.25°K) can be accounted for by introducing another mechanism. There is some indication that this mechanism is associated with amount of compensation.

The theoretical origins of the mechanisms are discussed. A theory is proposed to explain the concentration-dependent τ_S mechanism, according to which rapidly relaxing close pairs of phosphorus atoms, which are few in number, relax the spins of the large number of isolated phosphorus atoms via a spin diffusion process.

Experiments supporting this hypothesis are presented.

CROSS RELAXATION IN LiF. P. S. Pershan, Physics Department, Harvard University, Cambridge, Massachusetts (Received July 31, 1959).

A combined experimental and theoretical study of cross relaxation in LiF has been carried out. In agreement with theory, the cross relaxation time T_{21} is observed to be strongly anisotropic and field dependent; at 51.7 gauss it goes from 0.025 second in the [100] direction to 7 seconds in the [111] direction. A frequency distribution function analogous to the line shapes for magnetic absorption is measured down to 10^{-4} times the maximum value; for most orientations a Gaussian is an excellent approximation to it.

ELECTRICAL RESISTIVITY OF YTTRIUM SINGLE CRYSTALS. P. M. Hall, S. Legvold, and F. H. Spedding, Institute for Atomic Research and Department of Physics, Iowa State University, Ames, Iowa (Received July 27, 1959).

Two samples of yttrium cut from the same single crystal were used to determine the electrical resistivity parallel and perpendicular to the c axis of the hcp metal. Measurements were made over the temperature range from 1.3 to 300°K. A large anisotropy was observed, with $\rho_\perp/\rho_\parallel = 2.1$ at room temperature. Values for the polycrystalline resistivity over the temperature range indicated were computed from these data and were found to fit a Grüneisen law with $\theta = 187.5$°K. The computed polycrystalline values were also in good agreement with the measured resistivity of a polycrystalline sample.

FARADAY EFFECT IN CERIUM PHOSPHATE GLASSES AT LOW TEMPERATURES. Perry B. Alers, U. S. Naval Research Laboratory, Washington, D. C. (Received July 27, 1959).

The Faraday effect in glass specimens containing cerium metaphosphate in various concentrations has been measured at 4.2°K and 1.8°K, using 5461A light, in magnetic fields ranging to 70 kilogauss. The curves of rotation vs H/T were fitted to the Brillouin function for $J = 1/2$, yielding values of $g = 1.75$ and $\beta = 0.874$ Bohr magneton. The observed rotations were quite large; for the glass containing the highest concentration of cerium, the rotation approached a saturation value of 4.76π radians/mm.

PIEZORESISTANCE IN n-TYPE InP. A. Sagar, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania, and University of Pittsburgh, Pittsburgh, Pennsylvania (Received July 23, 1959).

Piezoresistance measurements were made on n-type InP at 77°K and 300°K. The results suggest a spherical energy band for this material.

THERMOLUMINESCENCE OF ZnS SINGLE CRYSTALS. H. Arbell and A. Halperin, Department of Physics, The Hebrew University, Jerusalem, Israel (Received July 29, 1959).

The blue and green components of the glow of ZnS:Cu:Cl crystals were recorded separately. Thermoluminescence-excitation spectra taken for each of the components were found to be identical with the excitation spectra for the blue and green luminescence at steady excitation. Other measurements included the spectral distribution of the glow, saturation effects, effects of infrared radiation, and computation of activation energies. The activation energy for the blue peak was found to be about 0.14 ev, and that for the green, about 0.20 ev. From the shape of the peaks it was concluded that the recombination process is bimolecular in character. Electrical glow curves were also recorded and were found to be similar to the green glow curves. The results are discussed and an energy model is proposed.

THEORY AND APPLICATION OF THERMALLY STIMULATED CURRENTS IN PHOTOCONDUCTORS. Rudolph R. Haering* and Edward N. Adams, International Business Machines Corporation, Research Laboratory, Poughkeepsie, New York (Received July 30, 1959; revised manuscript received August 24, 1959).

The theory of thermally stimulated currents is investigated in the limits of slow and fast retrapping. A method of obtaining the ionization energy E of the relevant traps is discussed. This method depends on the shift of the conductivity

maxima with heating rate and does not involve prior knowledge of the trapping cross sections or of the heating rate.

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SPIN RESONANCE OF TRANSITION METALS IN SILICON. H. H. Woodbury and G. W. Ludwig, General Electric Research Laboratory, Schenectady, New York (Received July 23, 1959).

Spin resonance measurements are reported for various charge states of four transition metals in silicon, namely for V^{++}, Cr^{+}, Mn^{-}, Mn^{++}, and Fe^{0}. In each case the g tensor and the hyperfine interaction with the impurity nucleus are isotropic. Thus each element exists in an isolated form in silicon and undergoes no distortion from the site of maximum symmetry. The site may either be the substitutional position or the interstitial position of maximum symmetry in the silicon lattice. For $(V^{51})^{++}$, $S=\frac{3}{2}$, $A=-42.10$; for $(Cr^{53})^{+}$, $S=\frac{5}{2}$, $a=+30.16$, $A=+10.67$; for $(Mn^{55})^{-}$, $S=1$, $A=-71.28$; for $(Mn^{55})^{++}$, $S=\frac{5}{2}$, $a=+19.88$, $A=-53.47$; for $(Fe^{57})^{0}$, $S=1$, $A=6.98$, where a is the cubic field splitting parameter, A is the hyperfine interaction of the isotope noted, and both are expressed in units of 10^{-4} cm^{-1}. Electron-nuclear double resonance was used for accurate measurement of A and for the determination of S. In the case of Fe, the electron spin was checked by noting that the iron line splits into two fine structure components under uniaxial stress. Association of Cr, Mn, and Fe with acceptors in silicon has been observed, as well as another charge state of isolated Fe.

MAGNETIC PROPERTIES OF HEMATITE SINGLE CRYSTALS. I. MAGNETIZATION ISOTHERMS, ANTIFERROMAGNETIC SUSCEPTIBILITY, AND WEAK FERROMAGNETISM OF A NATURAL CRYSTAL. S. T. Lin, Massachusetts Institute of Technology, Cambridge, Massachusetts (Received July 24, 1959).

Two sets of magnetization isotherms of pure natural hematite single crystals from Elba have been obtained in the temperature range from 488°K down to liquid helium temperatures. The first set of curves, along a certain direction in the basal plane, supports Néel's magnetic model of a superposition of a weak ferromagnetism on a normal antiferromagnetism. The second set of curves, along the ternary axis, displays very unusual form. The analysis of the isotherms shows that the antiferromagnetic susceptibility-temperature curves, $\chi - T$, are in good agreement with those obtained by Néel and Pauthenet but the weak ferromagnetic properties are apparently contradictory to their interpretations. The spontaneous magnetization-temperature curves, $\sigma_0 - T$, indicate that there is no isotropic ferromagnetism, and that the weak anisotropic ferromagnetism in the basal plane above transition and along the ternary axis below transition seems to have the same nature and origin. The $\chi - T$ and $\sigma_0 - T$ curves show that the wide transition takes place gradually and continuously. A general magnetic model of canted antiferromagnetism with unequal sublattice moments has been proposed which explains all the experimental data satisfactorily. From the present model, Haigh's data of remanent magnetization of hematite powder seem to be explained naturally.

EXPERIMENTAL INVESTIGATION OF CONDUCTION BAND OF GaSb. A. Sagar, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania, and University of Pittsburgh, Pittsburgh, Pennsylvania (Received July 24, 1959).

The conduction band of GaSb was investigated by making the following measurements on a number of n-type samples with different carrier concentrations: (1) Hall effect and conductivity between 1.5°K and 370°K, (2) the change of resistance and Hall effect of the samples under hydrostatic pressure (up to 14×10^{9} dynes/cm^2) at room temperature, and (3) the change of resistance due to uniaxial stress between 77°K and 370°K. Our data can be explained on the basis of a double conduction band for this material with the lowest band-minimum in the center of the Brillouin zone characterized by spherical constant-energy surfaces and the next minima along [111] directions in k-space characterized by ellipsoidal constant-energy surfaces. Our data can be further interpreted by assuming that the deformation potentials for the two bands in GaSb are similar to those of the corresponding bands in n-type germanium. The energy separation of the two bands at room temperature is estimated to be about 0.08 ev. The observed temperature dependence of the piezoresistance

could be explained by assuming that the energy separation ΔE changes with temperature at a rate $(d\Delta E/dT) \approx -3\times10^{-4}$ ev/°C. Throughout the analysis, the relaxation times for the electrons in the two bands were assumed to be independent of energy.

STRUCTURE OF *V* CENTERS IN IRRADIATED $KClO_3$. T. E. Hasty, W. B. Ard, Jr.,* and W. G. Moulton,† Department of Physics, University of Alabama, University, Alabama (Received March 23, 1959; revised manuscript received September 14, 1959).

On the basis of the electron spin resonance spectra of a single crystal of $KClO_3$ which has been exposed to x-irradiation, a model is proposed for the *V* center produced. The center proposed consists of a ClO radical covalently bonded to a neighboring ClO_3^- ion. It is shown that the electron spin resonance spectra predicted for this radical agree with the observed spectra, both in the number and spacing of the hyperfine components and their orientation dependence in the external magnetic field. It is also proposed that an O_2^- center is produced rather than the usual *F* center which one might expect to accompany the *V* center.

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POLARIZED LIGHT TRANSMISSION OF $BaTiO_3$ SINGLE CRYSTALS. R. C. Casella and S. P. Keller, International Business Machines Corporation Research Laboratory, Poughkeepsie, New York (Received July 22, 1959).

Optical transmission and reflection measurements were made on poled $BaTiO_3$ single crystals in the tetragonal phase (crystal class C_{4v}) with light polarized parallel and perpendicular to the *c* axis. The absorption coefficients, $\mu_\parallel$ and $\mu_\perp$, are presented as functions of the incident photon energy at room temperature. At the absorption edge, $\mu_\perp > \mu_\parallel$. A theoretical basis for this selection rule, which has been derived from first principles, is presented. The theory represents a generalization of earlier work on wurtzite crystals and extends the applicability of the wurtzite selection rule to all solids in the crystal classes C_{nv} and C_n, where $n = 3$, 4, or 6. Limitations of the theory are discussed. The dichroic effect in $BaTiO_3$ has also been studied experimentally at elevated temperatures, in the vicinity of the Curie point. It is concluded that the extrema of the valence and conduction bands of $BaTiO_3$ probably lie at (or very close to) the origin of the Brillouin zone.

EFFICIENCY OF ELECTROLUMINESCENCE IN ZnS. Gertrude Neumark, Solid State Laboratory, Sylvania Research Laboratories, Bayside, New York (Received July 20, 1959).

The efficiency of electroluminescence in ZnS is examined on the basis of a model of impact ionization in a barrier. On the basis of such a model, the efficiency depends on the ionization rate, and this rate has here been calculated by applying a theory developed for Ge and Si to ZnS. By considering the voltage dependence of the efficiency one can then get an estimate of a maximum obtainable efficiency in terms of the ratio of the barrier voltage to the total voltage. Both on the basis of this maximum efficiency and from other considerations it appears that the present theory can account for the magnitude of efficiencies reported to date.

LOW-TEMPERATURE MAGNETIC REMANENCE, MOLECULAR FIELD, AND APPROACH TO SATURATION OF HOLMIUM METAL. Warren E. Henry, United States Naval Research Laboratory, Washington, D. C. (Received July 31, 1959).

Magnetization approaching absolute magnetic saturation has been achieved for polycrystalline holmium metal. At 1.3°K and 70 000 gauss, the magnetic moment is approaching 4.0 Bohr magnetons per atom of holmium in contrast to the 10 Bohr magnetons per atom expected on the basis of the spectroscopically determined quantum numbers. The actual results are explained on the basis of crystalline electric field splitting of the ground term of holmium and application of the Pauli exclusion principle. In the liquid helium range, there is a pronounced hysteresis; i.e., the moment at 10 000 gauss is 50% higher in decreasing fields than in increasing fields. The remanence is 0.22 Bohr magneton per atom of holmium at 4.2°K and 0.42 Bohr magneton per atom at 1.3°K. A sample motion technique was used to measure the magnetic moment of the

5-gram sample. The equipment was calibrated with iron and nickel.

POSITRON ANNIHILATION IN METALS. S. Kahana, Department of Mathematics, McGill University, Montreal, Quebec, Canada (Received July 23, 1959).

A correlation function for a positron-electron pair within a metal is obtained by solving a Bethe-Goldstone equation. Thus one may take account of the many-body effects, of screening, and of the exclusion principle in computing the electron density at the position of the positron. The results indicate that one may in this fashion reconcile the Sommerfeld model of a metal with the experimental data on positron annihilation in metals.

THERMOELECTRIC EFFECTS IN COPPER-GOLD ALLOYS. M. D. Blue, Honeywell Research Center, Hopkins, Minnesota (Received July 22, 1959).

Measurements of the resistivity and thermoelectric power of the binary alloy CuAu and of CuAu alloys containing dilute amounts of Ni are analyzed using the thermoelectric power formula of Mott. At the transition temperature, anomalies in the thermoelectric power are observed. The scattering cross section and its derivative with respect to energy for Ni in CuAu are determined. The results are similar in value to these same parameters measured for dilute amounts of Ni in Cu.

THEORY OF DISPLACEMENT CASCADES IN COMPOUNDS. E. M. Baroody, Battelle Memorial Institute, Columbus, Ohio (Received July 23, 1959).

The theory undertakes the determination, for a simple model, of functions $N_{ik}(T)$ which represent the numbers of atoms of various kinds displaced when a primary atom receives an energy T. Assuming isotropic collisions involving pairs of free atoms, differential equations are formulated which contain concentrations, collision cross sections and mass ratios as parameters. Binding of the atoms is introduced through initial conditions which define threshold energies for displacement. Assuming a single threshold, linear equations for Laplace transforms are obtained and used to study the high-energy behavior of the functions. The effect of separate thresholds for the various kinds of atoms is examined for the case of equal masses.

Detailed calculations for diatomic solids indicate that cascades of moderate energy are rather well described by the high-energy equations and that the total number of displaced atoms is insensitive to mass ratio. Consideration of a monatomic solid with a spectrum of thresholds shows that such a solid should behave as though it possesses a single sharp threshold slightly below the mean of the spectrum.

MAGNETIC COUPLING IN CRYSTALLINE COMPOUNDS. A PHENOMENOLOGICAL THEORY OF MAGNETISM IN 3d METALS. E. O. Wollan, Oak Ridge National Laboratory, Oak Ridge, Tennessee (Received June 23, 1958; revised manuscript received March 9, 1959).

Magnetic coupling processes are considered in terms of the orbitals which result from the splitting of the d levels by the crystalline field. It is shown that the antiferromagnetic and ferromagnetic structure properties of many crystalline compounds can be qualitatively accounted for on the basis of indirect coupling processes which depend on the overlap of magnetic cation d orbitals with the p orbitals of intervening anions and on the electron spin occupation appropriate to the particular cations involved.

The orbital approach has also been used in considering the magnetic properties of the 3d metals and a coupling mechanism has been proposed which is consistent with much of the magnetic data relating to the iron group metals and their alloys.

MEASUREMENT OF EXCITATION OF N_2, CO, AND He BY ELECTRON IMPACT. G. J. Schulz, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania (Received July 17, 1959).

The inelastic excitation of N_2 and CO by electron impact is studied using the trapped-electron method. In this method those electrons which have lost a portion of their initial energy in an inelastic collision are trapped in a potential well. Well depths up to 3 volts are used in the present experiment. The operation of the apparatus is

checked for helium, where the shape of the excitation function is known accurately. The shape of the excitation function for metastable helium atoms obtained by the trapped-electron method is in good agreement with previous results. A large inelastic peak is observed at 2.3 ev in N_2 and 1.7 ev in CO. This phenomenon is discussed in terms of the formation of a temporary negative-ion state of N_2 or CO and subsequent decay into various vibrational levels of the molecule. This model explains the sharp peak in both the elastic and inelastic cross sections in N_2 and CO. Neither O_2 nor H_2 shows such a sharp peak at low energies.

ELECTRON SCATTERING BY NOBLE GASES IN THE LIMIT OF ZERO ENERGY. Bennett Kivel, AVCO-Everett Research Laboratory, Everett, Massachusetts (Received July 22, 1959).

The elastic scattering at zero energy by argon depends strongly on the polarization tail, since the contribution to the scattering length by forces inside the atom cancel. Assuming this is true for all noble gases one can approximate their zero-energy elastic cross section by $3.52\times10^{-6}\times(p/r_0)^2$ cm^2, where both p, the polarizability, and r_0, the size of the atom, are in atomic units. Using published values of the polarizability and scaling r_0 as the cube root of the atomic number from $r_0=8$ for argon, we find that this expression is consistent with existing experimental data. It is conjectured that the success of this approximation is a result of the Pauli exclusion principle.

CROSS SECTIONS FOR THE EXCITATION OF THE METASTABLE 2S STATE OF ATOMIC HYDROGEN BY ELECTRON COLLISION. William Lichten* and Sheldon Schultz, Columbia Radiation Laboratory, Department of Physics, Columbia University, New York, New York (Received July 6, 1959).

The function for excitation of the 2S state of atomic hydrogen by electron impact has been measured from threshold to 45 ev by an atomic beam method. The absolute value of the total cross section has been determined by two independent methods which are in agreement. In one method the excitation function was normalized to the Born approximation at the higher energies. The mechanism of cascade from higher P states was found to play a significant role in population of the metastable 2S level. The other method proceeded by determining the metastable detection efficiency in terms of the known efficiency for Lyman α photons. The yield for ejection of electrons from an untreated platinum surface by H(2S) is 0.065 ± 0.025. The total cross section reaches a maximum value of $(0.35\pm0.05)\pi a_0^2$ at 11.7 ev. The exchange cross section was also measured by the atomic beam method. The incident atoms were polarized in a Stern-Gerlach experiment; the metastable atoms were analyzed by the selective quenching action of a magnetic field of 575 gauss. The ratio of the exchange to total cross section is 0.45 ± 0.05 near threshold. At higher energies, this ratio approaches zero.

The cross section for production of metastable atoms by direct bombardment of molecular hydrogen is $0.03\pi a_0^2$. This value is considered correct to within a factor of two.

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μ-MESONIC MOLECULES. I. THE THREE-BODY PROBLEM. Stanley Cohen,* David L. Judd, and Robert J. Riddell, Jr.,† Radiation Laboratory, University of California, Berkeley California (Received July 27, 1959).

An approximate method is developed for treating a generalized hydrogen molecule ion in which two heavy particles have positive unit charges and one light particle has a negative unit charge. The expansion parameter of this approximation is the ratio of the light to the heavy mass. In first order, the method requires finding a solution to a pair of ordinary, second-order differential equations, which are coupled unless the masses of the heavy particles are equal. Explicit expressions for the coefficients in these equations are derived. The asymptotic forms of these coefficients for large nuclear separations give to first order the reduced-mass corrections to the binding energy of the light particle on either of the two heavy particles. The usual scattering theory is extended to obtain formulas for the various possible cross sections associated with this system. An iterative, variational technique for obtaining eigenvalues and eigenfunctions for bound states of the system is presented.

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μ-MESONIC MOLECULES. II. MOLECULAR-ION FORMATION AND NUCLEAR CATALYSIS.

Stanley Cohen,* David L. Judd, and Robert J. Riddell, Jr.,† Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received July 27, 1959).

The methods developed in the preceding paper are applied to the study of the behavior of μ mesons in liquid hydrogen. Numerically evaluated energy eigenvalues for the bound states of the various molecular-ion configurations are presented. Phase shifts and cross sections for the scattering of mesonic atoms from hydrogen and deuterium are given. It is shown that in the neighborhood of 0.2 ev the scattering of $(d\mu)$ atoms from protons exhibits a Ramsauer-Townsend effect with an anomalously small cross section occurring in this region. The existence of this effect provides an explanation for the appearance of "gaps" in the experimental observation of the catalytic process. The rate of exchange of mesons from protons to deuterons in pure deuterium is calculated along with the rates of formation of the $(p\mu p)^+$, $(p\mu d)^+$, and $(d\mu d)^+$ molecular ions. It is shown that the predominant mechanism for the formation of the molecular ions is dipole electron ejection. These results are shown to be in agreement with available experimental data. A semiphenomenological treatment of the (p,d) nuclear reaction is also given. A rough estimate of the γ-emission process indicates that the dominant mode of emission is from the singlet proton spin states.

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CROSS SECTIONS AND ANGULAR DISTRIBUTIONS FOR THE $B^{10}(\alpha,d)C^{12}$ REACTION FROM 3.1 Mev TO 3.7 Mev.

Kazuo Ôno and Keiichi Kuroda, Institute for Solid State Physics, University of Tokyo, Tokyo, Japan
(Received July 29, 1959).

In order to investigate the possibility of direct interactions in (α,d) reactions, the $B^{10}(\alpha,d)C^{12}$ reaction has been studied from an alpha-particle bombarding energy of 3.1 to 3.7 Mev. The yield curves are rather flat and show no typical resonance structures. Angular distributions show a peak at about $\theta_{c.m.} = 70°$ and an increase of intensity in the backward direction over the entire alpha-particle energy range. These results indicate that the $B^{10}(\alpha,d)C^{12}$ reaction proceeds mostly by direct processes, probably both knock-on and heavy-particle stripping ones.

CALORIMETRIC DETERMINATION OF THE AVERAGE TOTAL KINETIC ENERGY OF FRAGMENTS FROM FISSION OF U^{235} AND U^{238} BY 14-Mev NEUTRONS.

P. C. Stevenson, H. G. Hicks, J. C. Armstrong, Jr., and S. R. Gunn, Lawrence Radiation Laboratory, University of California, Livermore, California
(Received July 17, 1959).

The fission yields of Mo^{99} from 14-Mev neutron bombardments of U^{235} and U^{238} were found to be $(5.01 \pm 0.15)\%$ and $(5.86 \pm 0.16)\%$, respectively. The average total fragment kinetic energies released in fission of U^{235} and U^{238} were found to be 174 ± 4 and 175 ± 2 Mev, respectively.

EXCITED STATES OF B^{13}.

G. C. Morrison and J. A. Galey, Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received July 20, 1959).

The energy levels in B^{13} up to an excitation energy of 6 Mev have been investigated by means of the reaction $Li^7(Li^7,p)B^{13}$ at an energy of 2 Mev for the incident Li^7 ions. Selection and identification of the outgoing protons in the presence of deuterons, tritons, and alpha particles emitted in competing reactions is achieved with a proportional counter-CsI(Tl) scintillation counter telescope system which gives a measure of the dE/dx and E of the emitted particle. From the observed energy spectrum of protons emitted at 90°, the Q-value of the reaction leading to the ground state of B^{13} was determined to be 5.97 ± 0.05 Mev in agreement with a previous measurement by Norbeck, and the energy of excitation of the first four levels in B^{13} were determined to be 3.70 ± 0.05 Mev, 4.16 ± 0.05 Mev, 5.05 ± 0.08 Mev, and 5.5 ± 0.1 Mev. At 90° in the laboratory system the relative intensities of the proton groups leading to the ground state and first four excited

states are in the ratio of 1.0:2.6:0.8:1.6:1.0, respectively.

ANGULAR DISTRIBUTION OF Li^8 FROM $Be^9(Li^7, Li^8)Be^8$. E. Norbeck, J. M. Blair, L. Pinsonneault, and R. J. Gerbracht, School of Physics, University of Minnesota, Minneapolis, Minnesota (Received July 21, 1959).

Angular distribution curves and an excitation curve are given for Li^8 produced by the reaction $Be^9(Li^7, Li^8)Be^8$ with Li^7 beam energies between 2.0 and 4.0 Mev. The angular distribution may be roughly approximated by $\sin^2\theta$ in the center-of-mass system, with the central peak shifting forward as the energy is increased. The total cross section for the production of Li^8 increases with energy with no indication of resonances.

RADIATIVE PROTON CAPTURE BY O^{18}. J. W. Butler and H. D. Holmgren, Nucleonics Division, United States Naval Research Laboratory, Washington, D. C. (Received July 20, 1959).

A search for gamma-emitting levels in F^{19} between 8.3 and 9.8 Mev of excitation energy has been made by bombarding a NiO target (39% O^{18}) with protons over the energy range 360 to 1960 kev. Resonances in the gamma-ray yield were observed with the use of a 3-in. diam×3-in. sodium iodide crystal and a 20-channel pulse-height analyzer. The results are as follows:

Resonance energy (kev)	Resonance width (kev)	γ-ray energies (Mev)
630 ± 2	2.6 ± 1.0	8.5 ± 0.2
849 ± 3	40 ± 5	8.5 ± 0.3, 7.2 ± 0.2, 4.8 ± 0.2, 4.3 ± 0.2(?), 2.4 ± 0.2(?)
1169 ± 2	≈0.9	8.8 ± 0.2, 7.7 ± 0.2, 6.27 ± 0.05, 3.67 ± 0.05, 2.59 ± 0.05, 1.24 ± 0.05
1399 ± 5	<15	...
1685 ± 5	<15	...
1769 ± 2	4.0 ± 1.0	9.4 ± 0.3
1931 ± 2	1.5 ± 1.0	9.8 ± 0.2, 8.45 ± 0.10

The angular distribution of the 6.27-Mev gamma ray from the 1169-kev resonance was measured, and the results are listed in tabular form. The results of the present experiment are compared with other experiments using the $O^{18}(p,\gamma)F^{19}$, $O^{18}(p,\alpha)N^{15}$, and $O^{18}(d,n)F^{19}$ reactions.

CONSERVATION OF PARITY IN STRONG INTERACTIONS. R. Haas,* L. B. Leipuner, and R. K. Adair, Brookhaven National Laboratory, Upton, New York (Received July 16, 1959).

An investigation was made of the angular distribution of the gamma rays produced by the capture of slow polarized neutrons in cadmium, indium, and silver. The portion of the intensity of the transitions from the spin-one capture state of Cd^{114} to the spin-zero ground state and spin-two first excited state, which is proportional to $\cos\theta$, where θ is the angle between the neutron spin and the direction of propagation of the gamma ray, was measured to be less than one part in 10^3. From this result the conclusion is reached that the intensity of the odd-parity part of the neutron capture state is less than 2×10^{-3} times as large as the even-parity part, and that the parity-nonconserving part of nuclear forces is less than 10^{-8} times as strong as the parity-conserving part. Qualitatively similar, though weaker, conclusions were derived from the measurements on silver and indium.

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NEUTRON YIELDS FROM TARGETS BOMBARDED BY ELECTRONS. W. C. Barber and W. D. George, High-Energy Physics Laboratory, Stanford University, Stanford, California (Received July 21, 1959).

The total neutron yields from thick targets bombarded by electrons were measured as a function of electron energy for the range 10 to 36 Mev. Targets ranging in thickness from one to six radiation lengths of C, Al, Cu, Ta, Pb, and U were used. The yields for 1- and 6-radiation-length targets of Pb at 34 Mev are 2.1×10^{-3} and 9.0×10^{-3} neutron/electron. Extrapolation to infinite target thickness gives a value of 9.5×10^{-3} neutron/electron. The yield, comparing targets of one radiation length, from C is about 10 times smaller and that from U two times greater than the yield from Pb. An ex-

planation of the relative Z dependence of the yield in terms of known photonuclear cross sections is successful to within a factor of 1.5. The absolute accuracy of the results is estimated to be $\pm 15\%$.

Calibration of the neutron-detecting equipment was made with a Ra-Be source and checked by measuring the yields, due to electro- and photodisintegration of the deuteron, from a heavy-water target. In addition, yields from thin targets of Be and Cu were observed as a function of electron energy. The data for Be yield a value of (0.018 ± 0.003) Mev-barn for the (γ, n) cross section integrated to 17 Mev. The data for Cu were analyzed and combined with other measurements to give an approximate cross section for the $Cu(\gamma, pn)$ reaction.

PLANE POLARIZATION OF 15.1-Mev BREMSSTRAHLUNG FROM 25-Mev ELECTRONS. D. Jamnik* and P. Axel, Physics Department, University of Illinois, Urbana, Illinois (Received July 20, 1959).

Linearly polarized gamma rays were produced with the aid of a special betatron doughnut which made it possible to limit the effective thickness of the bremsstrahlung-producing Al and Pt targets. The linear polarization of 15.1-Mev bremsstrahlung gamma rays was detected by measuring the azimuthal angular distribution of gamma rays which had been scattered elastically from the well-known nuclear level in C^{12}.

For the particular effective thickness of Al that was used, the maximum polarization of 15.1-Mev gamma rays in the bremsstrahlung of 25-Mev electrons was 1.53 ± 0.05. (This corresponds to 21% in the more conventional polarization notation.) Both this observed maximum (which occurred at an angle of 1.4°) and the polarization measured at four other angles confirm theoretical predictions.

With the platinum target that was used, the observed polarization of 1.28 ± 0.04 was about 10% lower than the value predicted by theoretical calculations which use the Born approximation and neglect screening. However, available screening and Coulomb corrections bring the theoretical predictions into essential agreement with the experimental values.

Since the elastic scattering pattern of gamma rays shows unambiguously that the strong photon scattering level at 15.1 Mev in C^{12} is excited by magnetic dipole radiation, this level has spin 1 and even parity.

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DETECTION OF THE FREE ANTINEUTRINO. F. Reines,* C. L. Cowan, Jr.,† F. B. Harrison, A. D. McGuire, and H. W. Kruse, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico (Received July 27, 1959).

The antineutrino absorption reaction $p(\bar{\nu}, \beta^+)n$ was observed in two 200-liter water targets each placed between large liquid scintillation detectors and located near a powerful production fission reactor in an antineutrino flux of 1.2×10^{13} cm^{-2} sec^{-1}. The signal, a delayed coincidence event consisting of the annihilation of the positron followed by the capture of the neutron in cadmium which was dissolved in the water target, was subjected to a variety of tests. These tests demonstrated that reactor-associated events occurred at the rate of 3.0 hr^{-1} for both targets taken together, consistent with expectations; the first pulse of the pair was due to a positron; the second to a neutron; the signal depended on the presence of protons in the target; and the signal was not due to neutrons or gamma rays from the reactor.

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THE REACTION $C^{12}(d, n)N^{13}$. A. Elwyn,* J. V. Kane, S. Ofer,† and D. H. Wilkinson,‡ Brookhaven National Laboratory, Upton, New York (Received July 30, 1959).

The reaction $C^{12}(d, n)N^{13}$ has $Q = -0.28$ Mev and so is expected to show strong direct-interaction effects even at low energies of the bombarding deuterons. We have made an extensive study of this reaction at 14 values of the deuteron energy between $E_d = 1.45$ Mev and $E_d = 2.95$ Mev. At each deuteron energy the differential cross section was measured at about 20 angles between 0° and 165°. Neutron time-of-flight techniques were used and each point on each angular distribution represents the detection of at least 10^3 neutrons.

Direct interaction effects are seen at all bombarding energies in the backward as well as in the forward hemisphere. The differential cross section at 0° shows very pronounced "resonance" structure but this largely disappears in the integrated cross section and is due chiefly to interference between the direct interaction term and the probably quite small compound nucleus contribution. A rough method for eliminating the interference terms between the two mechanisms in the differential cross section is proposed and applied. The resultant "purified" angular distribution is remarkably close, in the forward hemisphere, to that predicted by simple stripping theory. A backward maximum, much lower than the forward peak, is also present but not accounted for.

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DIFFERENTIAL CROSS SECTIONS FOR THE $Be^9(He^3, p)B^{11}$ REACTION. E. A. Wolicki, H. D. Holmgren, R. L. Johnston, and E. Geer Illsley,* Nucleonics Division, United States Naval Research Laboratory, Washington, D. C. (Received July 17, 1959).

The differential cross sections for the six highest energy proton groups from the $Be^9(He^3, p)B^{11}$ reaction have been measured as a function of angle at a bombarding energy of 4.5 Mev. For the five highest energy groups, the cross sections are largest in the forward direction and are not symmetric about 90°. For all six proton groups, yields observed at large angles to the incident beam direction are comparable to the forward yields. A strong maximum in the backward direction is observed for the third excited state proton group. At 4.5 Mev, the total cross sections are 11.5 millibarns for the ground-state proton group and 7.4 millibarns for the first excited state proton group. For the proton groups leaving B^{11} in the ground and first excited states, differential cross sections have been measured at six angles as a function of bombarding energy in the range from 1.8 to 5.0 Mev. In each case, the total cross section for the reaction shows no resonances. The change in the angular distributions which may be inferred from these yield curves is seen to proceed in a gradual manner with increasing bombarding energy. Differential cross sections for the second and third excited state proton groups were measured at 7° and 90° in the bombarding energy interval from 3.0 to 5.0 Mev. The observed characteristics for this reaction taken together indicate that direct interactions are important

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SINGLE-PARTICLE ENERGIES IN THE THEORY OF NUCLEAR MATTER. K. A. Brueckner and D. T. Goldman, Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania (Received July 20, 1959).

The excitation spectrum of real and virtual excitations is discussed from the point of view of the perturbation series expansion. The effect of the rearrangement energy terms in the single-particle virtual excitation spectrum is evaluated and seen to be very small. It is also noted that the virtual particle energies are real due to the effects of off-energy-shell propagation.

Starting from the reaction matrix approximation for the ground-state energy, the energies of real particle and hole excitations are defined which satisfy the separation energy theorem. It is shown that the energies so defined depend on an infinite sequence of terms giving the rearrangement energy for multiple excitations. Appropriate termination and evaluation of this series are discussed.

LEVELS OF P^{29} FROM $Si^{28}(p,p)Si^{28}$ AND $Si^{28}(p, p')Si^{28*}$. J. Vorona,* J. W. Olness,† W. Haeberli,‡ and H. W. Lewis, Duke University, Durham, North Carolina (Received July 22, 1959).

Differential cross sections for the elastic and inelastic scattering of protons from Si^{28} have been measured at center-of-mass scattering angles of 167.7°, 141.3°, 90.0°, and 54.7° for proton energies between 1.4 and 3.8 Mev. Resonances were observed at proton energies of 1.66, 2.09, and 2.88 Mev, in addition to the resonances at 3.10, 3.34, 3.58, and 3.71 Mev which correspond to levels in P^{29} reported previously by other investigators from studies of the gamma rays from $Si^{28}(p,p'\gamma)Si^{28}$. Differential cross sections and angular distributions for inelastic

scattering to the 1.78-Mev first excited state of Si^{28} were also measured for proton energies above 3 Mev. Measurements were made with a gas scattering chamber containing silane (SiH_4) as the target gas. The elastic scattering data were analyzed in terms of the single-level approximation of the dispersion theory to determine the resonance parameters. This analysis, together with the analysis of the inelastic scattering cross sections and angular distributions, has resulted in the following assignments of resonance energies (Mev) and spins and parities for the resonance levels of P^{29}: 1.660 ($3/2^-$); 2.090 ($1/2^+$); 2.88 ($1/2^-$); 3.100 ($5/2^-$); 3.337 ($3/2^+$); 3.575 ($3/2^-$); and 3.711 ($3/2^+$). The large reduced elastic scattering widths of the p-wave resonances at 1.660 and 2.88 Mev suggest that these levels correspond to single-particle excitations of P^{29}.

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DIFFERENTIAL ELASTIC SCATTERING OF 14-Mev NEUTRONS BY Zn, Sn, Sb, Pb, AND Bi. L. A. Rayburn, Argonne National Laboratory, Lemont, Illinois (Received July 20, 1959).

Differential elastic scattering cross sections in the angular interval from 10° to 165° have been measured for Zn, Sn, Sb, Pb, and Bi. The experimental measurements are corrected for multiple scattering and the finite angular resolution by Monte Carlo methods. The corrected cross sections are compared with theoretical values computed by use of a complex potential with a spin-orbit term.

COULOMB EXCITATION OF NUCLEI BY Li^6 AND Li^7 PROJECTILES. C. S. Littlejohn and G. C. Morrison, Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois (Received July 29, 1959).

In order to examine the characteristics of lithium-ion induced Coulomb excitation, and to extend the cross-section ratio technique for the determination of the multipolarity of transitions, a study has been made of the gamma rays emitted following electric excitation of several different target nuclei by Li^6 and Li^7 ions in the energy range 1.1 to 2.2 Mev. Measurements have been made of thick target yields of the 110-kev ($E1$) and 198-kev ($E2$) gamma rays from F^{19}, the 128-kev ($E2$) gamma ray from Mn^{55}, and the 160-kev ($E2$) gamma ray from Ti^{47}, and compared with yields calculated from the theoretical cross sections. The yields of the gamma rays studied were observed to increase with beam energy in the manner predicted by theory for electric dipole or electric quadrupole excitation. The ratio of the Li^6 and Li^7 induced yields at corresponding (equal ξ) energies for $E1$ and $E2$ transitions after correction for range effects were found to agree, within the estimated errors, with the theoretical predictions for cross-section ratios.

DIRECTIONAL AND POLARIZATION CORRELATION MEASUREMENTS ON Eu^{152m}. G. T. Wood,* Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark (Received July 31, 1959).

The spins and parities of the 1511-kev level in Sm^{152} and the 1315-kev level in Gd^{152} are discussed on the basis of directional correlation and polarization-direction correlation measurements on the 1389-122 kev and 970-344 kev gamma-gamma cascades, following the decay of 9-hour Eu^{152m}. Both levels have been assigned spin and parity 1^-. In order to check the apparatus on cascades known on the basis of previous measurements, directional and polarization-direction correlation measurements have also been made on the 842-122 kev (from 9-hour Eu^{152m}) and 1409-122 kev (from 12-year Eu^{152}) cascades in Sm^{152}.

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NEUTRONS FROM THE PROTON BOMBARDMENT OF Li^6 AND Li^7. F. Ajzenberg-Selove and C. F. Osgood, Haverford College, Haverford, Pennsylvania, and C. P. Baker, Brookhaven National Laboratory, Upton, New York (Received July 31, 1959).

The $Li^7(p,n)Be^7$ and $Li^6(p,n)Be^6$ reactions were studied at $E_p = 10.5$ Mev, by the method of proton recoils in nuclear emulsions. The $Li^7(p,n)Be^7$ spectra at 30° and 90° show the known states of Be^7 at 0, 0.43, and 4.53 Mev. The

cross section for formation of the ground state at 90° (lab) is 3.2 mb/sterad (±30%). The $Li^6(p, n)Be^6$ spectra at 30°, 60°, 90°, and 135° show ground-state groups with $Q = -5.05 \pm 0.2$ Mev. This leads to $(M\text{-}A)$ for $Be^6 = 20.13 \pm 0.2$ Mev. $Be^6(0)$ is thus unbound with respect to $(He^4 + 2p)$ by 1.35 Mev. The cross section for formation of $Be^6(0)$ at 90° (lab) is 0.5 mb/sterad (±30%). At 90°, there is also indication of a sharp excited state at $E_x = 1.5 \pm 0.2$ Mev. The lifetimes of $Be^6(0)$ and $Be^6(1.5$ Mev) are $\gtrsim 4 \times 10^{-21}$ sec and $> 7 \times 10^{-21}$ sec, respectively. These results are discussed in terms of the other available information on the $A = 6$ isobars.

SEARCH FOR LOW-ENERGY GAMMA RAYS IN O^{16}. William W. Pratt, Department of Physics, The Pennsylvania State University, University Park, Pennsylvania, and Robert G. Cochran,* College of Engineering and Architecture, The Pennsylvania State University, University Park, Pennsylvania (Received July 29, 1959).

In the expectation that at least one low-energy transition from the fourth excited state of O^{16} may compete to an observable extent with the 7.11-Mev ground-state transition, a search was made for the 0.97-Mev $(1^- \rightarrow 3^-)$ and the 1.05-Mev $(1^- \rightarrow 0^+)$ gamma rays. Limiting values, $I(7.11)/I(0.97) > 200$ and $I(7.11)/I(1.05) > 370$, were found for the branching ratios.

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NEUTRON-INDUCED FISSION CROSS SECTION OF Np^{237}. H. W. Schmitt and R. B. Murray, Oak Ridge National Laboratory, Oak Ridge, Tennessee (Received July 27, 1959).

The neutron-induced fission cross section of Np^{237} has been measured as a function of neutron energy in the range 0.9 to 8.0 Mev. Measurements above 1.7 Mev were made relative to the fission cross section of U^{238} using 2π-counting of fission fragments from thin fissile deposits placed back to back in a gridded ionization chamber. In the range 0.9 to 2.8 Mev the energy dependence of the Np^{237} fission cross section was determined relative to the $T(p, n)He^3$ yield, and the results were normalized to those of the comparison counting experiment in the overlapping energy range. Results show that the cross section increases above threshold to a maximum value of 1.75 barns at ~2 Mev, decreases to 1.40 barns at ~5 Mev, and increases again to 2.14 barns at 8 Mev. Estimated uncertainty in the absolute magnitude of $\sigma_f(Np)$ is ±7%.

ISOMERIC LEVEL IN Pb^{205} FORMED IN THE DECAY OF Bi^{205}. Stanley H. Vegors, Jr.,* and R. L. Heath, Atomic Energy Division, Phillips Petroleum Company, Idaho Falls, Idaho (Received July 24, 1959).

An activity of 4.8-msec half-life which is assigned to Pb^{205m} has been observed in the electron-capture decay of 14.5-day Bi^{205}. This isomeric level decays with the emission of 987.8, 703.3, and 284.4-kev gamma rays with relative transition intensities of 100, 10, and 10. No other gamma rays of energy greater than 10 kev were observed in the decay of this isomer. The 284.4- and 703.3-kev gamma rays are in coincidence but neither is in coincidence with the 987.8-kev transition. This evidence suggests that the 987.8-kev level de-excites directly to the ground state by the emission of a 284.4, 703.3-kev cascade with a 987.8-kev crossover. There is some evidence (not conclusive) that the 987.8-kev level itself may not be isomeric but that it may be fed entirely by a highly converted low-energy transition (< 100 kev) from an isomeric level.

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RESONANCE FISSION WIDTHS OF U^{235} FOR LEVELS FROM 6 ev TO 50 ev. W. W. Havens, Jr., E. Melkonian, L. J. Rainwater, and J. L. Rosen, Columbia University, New York, New York (Received July 30, 1959).

The energy variation of the total and fission cross sections of U^{235} has been measured with the Nevis synchrocyclotron neutron velocity spectrometer. Fission widths for most of the levels up to 50 ev have been deduced from these measurements. The distribution of the 38 known fission widths shows that the number of channels available for the fission process is between one and four and is most probably two. If $\overline{\Gamma}_f$ is different for the two possible spin states of the compound nucleus, these cannot differ by more than an order of magnitude.

MULTIPLE MESON PRODUCTION IN NUCLEON-NUCLEON INTERACTIONS AT ENERGIES OF 10^{12} ev. Marcel Schein, D. M. Haskin, E. Lohrmann, and M. W. Teucher, Department of Physics, University of Chicago, Chicago, Illinois (Received July 13, 1959).

A nuclear interaction of type $0+20p$ observed in nuclear emulsion was analyzed by measuring the energies and angles of the secondary particles. The primary energy, as determined from the angular distribution of the tracks, is 2.7×10^{12} ev. This value is in agreement with an independent estimate obtained from the total energy dissipated. A secondary collision of type $0+20n$ was also analyzed in the same way. Its energy is 1.4×10^{12} ev, which is comparable to the primary energy. The inelasticity of the primary event is $0.54^{+0.16}_{-0.19}$.

Energy and angular distributions of the shower particles in the center-of-mass (c.m.) system are given for both events. The shower particles show a correlation in the sense that those with the highest energies are emitted in the c.m. system under small angles with the shower axis.

The energy distribution of the mesons in the c.m. system is peaked toward low energies and shows a remarkably long tail at high energies extending up to 10 Bev. One of these particles is a π^0 meson, which carries off about 23% of the total energy.

The average value of the transverse momentum of the shower particles is 0.3 ± 0.05 Bev/c.

MODIFIED ANALYSIS OF NUCLEON-NUCLEON SCATTERING. II. COMPLETED ANALYSIS OF p-p SCATTERING AT 310 Mev. Malcolm H. MacGregor, Michael J. Moravscik, and Henry P. Stapp, Lawrence Radiation Laboratory, University of California, Livermore and Berkeley, California (Received May 28, 1959).

The application of a recently suggested modified method of analysis of nucleon-nucleon scattering experiments to p-p scattering at 310 Mev has been completed. The results are summarized and compared with the work of Gammel and Thaler and of Signell and Marshak. The analysis is carried out on several levels, with varying number of angular-momentum states being described by phenomenological phase shifts while the higher angular-momentum states are represented by the one-pion exchange contribution. It is found that the inclusion of the high angular-momentum states in this manner makes a significant improvement in the analysis. The pion-nucleon coupling constant is also determined from the data with a fair accuracy. The five "best" sets of phase shifts of the conventional analysis are reduced to two sets, corresponding to Solution 1 and 2 of the conventional analysis. Some slight evidence favors Solution 1 over Solution 2. It is shown that a very satisfactory fit can be obtained with 9 parameters instead of the 14 parameters of the conventional analysis. Some remarks are made about the extent to which Solutions 1 and 2 are distinct. Experiments are suggested which could resolve the remaining ambiguity due to the existence of two sets of phase shifts.

STABILITY OF THE ADIABATIC MOTION OF CHARGED PARTICLES IN THE EARTH'S FIELD. Theodore G. Northrop and Edward Teller, Lawrence Radiation Laboratory, University of California, Livermore, California (Received July 20, 1959).

The motion of charged particles in a magnetic field such as that of the earth or that of a magnetic mirror machine is discussed. It is shown that during the motion and drift of a relativistic particle, not only the magnetic moment, but also a longitudinal invariant and an additional flux invariant are adiabatically conserved. These conservation laws lead to retention of the particles in the field. The derivation of the adiabatic invariants leads to a set of equations of motion which describe the average drift of the particles from one force line to the other, and which also describe the changes that occur in the energies and periods associated with the motion. In the absence of scattering, loss of particles from the magnetic field will be due to the violation of the adiabatic laws.

MUON CAPTURE BY C^{12} AND BETA DECAY OF B^{12}. G. Flamand, Palmer Physical Laboratory, Princeton University, Princeton, New Jersey, and K. W. Ford, Brandeis University, Waltham, Massachusetts (Received July 23, 1959).

The finite size of the carbon nucleus causes the K-orbit muon density within the nucleus to be smaller than the density for a point nucleus. Previously calculated muon capture rates in car-

bon should be reduced by about 6% for this effect. Our recalculated capture rate to the ground state of B^{12} does not differ greatly from previously calculated values. It is 7300 sec^{-1}, with an assigned theoretical error of about 10%. The result tends to support the Feynman–Gell-Mann proposal of a conserved vector current in the framework of a universal Fermi interaction. We give also various predicted correlation coefficients, which do not differ significantly from those of Wolfenstein.

The allowed and all second-forbidden matrix elements have been calculated as functions of the intermediate coupling parameter a/K. The beta decay rate of B^{12} is predicted correctly for $a/K = 4.5$, a value which is close to that favored by other evidence. The calculated second-forbidden vector matrix element differs by 20% from the "experimental" value derived from a magnetic dipole transition rate in C^{12}.

PION-PROTON SCATTERING BELOW 150 Mev. S. W. Barnes, B. Rose,* G. Giacomelli,† J. Ring, K. Miyake, and K. Kinsey, University of Rochester, Rochester, New York (Received July 16, 1959).

Positive-pion proton differential cross sections have been measured at 41.5 Mev for six angles. The angles in the center-of-mass system are 53°, 69.1°, 100.4°, 128°, 141.7°, and 163.5° and the corresponding cross sections in mb/sterad in the center-of-mass system are 0.252 ± 0.020, 0.354 ± 0.025, 0.777 ± 0.038, 1.145 ± 0.067, 1.495 ± 0.084, and 1.750 ± 0.110. Negative-pion elastic scattering cross sections have been measured for the first five of the above angles and are, respectively, in mb/sterad in the c.m. system: 0.338 ± 0.047, 0.281 ± 0.038, 0.148 ± 0.029, 0.112 ± 0.042, and 0.085 ± 0.025. Phase shift analyses of these data and those of other authors lead to the following expressions for the low-energy behavior of the $T = \frac{3}{2}$ phases:

$$\alpha_{31}^{N} = -(0.0418 \pm 0.004)\eta^3,$$

$$\alpha_{3}^{N} = -(0.1145 \pm 0.0026)\eta,$$

and

$$\cot\alpha_{33}^{N} = \tfrac{4}{3}\eta^3(0.0877 \pm 0.0014)/[\omega^*(1 - \omega^*/2.17)].$$

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PION-PROTON SCATTERING BELOW 150 Mev. S. W. Barnes, H. Winick, K. Miyake, and K. Kinsey, University of Rochester, Rochester, New York (Received July 16, 1959).

Values found for 30-Mev scattering at the two center-of-mass angles 116.8° and 155° are, respectively, for positive pions 0.849 ± 0.048 and 1.098 ± 0.075 mb $sterad^{-1}$, and for negative pions of the same energy 0.187 ± 0.020 and 0.165 ± 0.022 mb $sterad^{-1}$. Phase-shift analyses are made of recent published π^- distributions in the above energy range and serve to furnish prescriptions for the low-energy behavior of the $T = \frac{1}{2}$ phases. Calculations of σ^{--}, σ^{-0}, and $\sigma^{-}_{\text{total}}$ at various energies agree with measurements found in the literature. An essential agreement is found between $\pi^- + p$ forward scattering amplitudes and a dispersion equation over this energy region.

$\pi^{\pm}$-p ELASTIC SCATTERING AT 30 Mev. G. Giacomelli,* Department of Physics, University of Rochester, Rochester, New York (Received July 16, 1959).

Differential scattering cross sections in hydrogen for (30 ± 1.5)-Mev positive and negative pions have been measured at the two center-of-mass angles of 82 and 99.9 degrees.

The cross sections for positive pions in mb/sterad in the center-of-mass system are 0.435 ± 0.028 and 0.590 ± 0.030, for negative ones 0.268 ± 0.028 and 0.239 ± 0.021, respectively.

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STRUCTURE OF THE FORWARD SCATTERING AMPLITUDE. Stanley Deser, Department of Physics, Brandeis University, Waltham, Massachusetts, and Walter Gilbert and E. C. G. Sudarshan,* Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts (Received May 15, 1959).

The matrix elements of various products of two currents between states of equal energy-momentum are studied. Use of the axioms of local field theory leads to an integral representation for the Fourier transform of matrix elements of the retarded commutator in terms of two invariant momentum parameters. Further restrictions on the class of allowed functions permits explicit incorporation of the mass restric-

tions as support conditions on the weight function. The "bound-state" term is separated off and related to the vertex functions. As a simple application, forward-scattering dispersion relations are derived by specialization of the Green's function. In particular, these can be obtained for nucleon-nucleon and K-meson–nucleon scattering.

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MESON-NUCLEON SCATTERING AND NUCLEAR FORCES. Victor F. Weisskopf, Department of Physics and Laboratory of Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts (Received July 16, 1959).

A simple derivation which does not make use of field theory is given of the main results of the static theory of π-meson scattering by nucleons. The derivation serves to elucidate the connection between low-energy meson scattering and the nuclear forces at large distances.

MAGNETIC MOMENT OF THE DEUTERON. H. D. Young and R. E. Cutkosky, Carnegie Institute of Technology, Pittsburgh, Pennsylvania (Received July 23, 1959).

A contribution to the deuteron magnetic moment which results from the altered expectation values of nucleon core spins in the bound state is calculated. The adiabatic approximation, in which the π-meson clouds of a static-nucleon model are assumed to follow the orbital motion of the sources, is used. The two-nucleon states are expanded in Heitler-London states; the expectation value of the deuteron magnetic moment operator is related to single-nucleon matrix elements by means of an expansion corresponding to exchange of various numbers of mesons between the nucleons. The single-nucleon matrix elements are evaluated using the Chew-Low-Wick fixed-source theory. If an orbital wave function with a relatively large D-state probability is used, the one-meson exchange terms give an increase in the deuteron magnetic moment of about one percent. The two-meson exchange terms are considerably smaller than the one-meson exchange terms.

GEOMETRICAL REPRESENTATION OF THE MAXWELL FIELD IN MINKOWSKI SPACE. Edward S. Lowry, International Business Machines Corporation, Poughkeepsie, New York (Received July 23, 1959).

The electromagnetic field tensor of a classical charged particle is associated with the orientation and density of a family of two-dimensional surfaces radially distributed about the world line of the particle in Minkowski space.

MASS SPLITTINGS WITHIN BARYON CHARGE MULTIPLETS. R. E. Behrends* and L. Landovitz, Brookhaven National Laboratory, Upton, New York (Received July 30, 1959).

We have calculated the effect upon the mass splittings within each isobaric multiplet of a phenomenological boson mass difference. It has been possible to sum the diagrams to all orders in the strong couplings but the results are only valid to first order in the mass difference. These results can be compactly expressed as derivatives with respect to the intermediate masses of a function related to the proper self energy. The second order perturbation results are also calculated.

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AUTHOR INDEX TO VOLUME 3

References with (E) are to Errata

ABASHIAN, ALEXANDER (see Haddock, Roy P.) 478
ADAIR, ROBERT K. Capture in (K^-, p) atoms 438
ADAM, J. and B. COX. Neutron and fission fragment damage in zirconia 543
AGNEW, L. (see Elioff, T.) 285
ALBENESIUS, E. L. Tritium as a product of fission 274
ALBURGER, DAVID E. 7.656-Mev $E0$ transition in C^{12} 280
ALERS, G. A. (see Neighbours, J. R.) 265
ALFVÉN, HANNES. Momentum spectrum of the Van Allen radiation 459
ANDERSON, C. E., W. J. KNOX, A. R. QUINTON, and G. R. BACH. Nuclear fragments produced in the heavy ion bombardment of aluminum 557
ANDERSON, F. (see Block, M. M.) 291
ANDERSON, P. W. Knight shift in superconductors 325
ARP, V., D. EDMONDS, and R. PETERSEN. Hyperfine coupling in CoFe and CoNi alloys as determined by heat capacity measurements 212
ASTBURY, A., I. M. BLAIR, M. HUSSAIN, M. A. R. KEMP, H. MUIRHEAD, and R. G. P. VOSS. Angular distribution of neutrons following the nuclear capture of polarized muons 476

BACH, G. R. (see Anderson, C. E.) 557
BADESSA, R. S., R. L. KENT, and J. C. NOWELL. Short-time measurement of time dilation in an earth satellite 79
BAKER, J. (see Lambe, J.) 270
BAKER, W. F. and C. RUBBIA. Neutron asymmetry from μ capture in magnesium 179
BARNES, R. G. and S. L. SEGEL. Pure nuclear quadrupole resonances in paramagnetic iron-group halides 462
BASHKIN, S., R. W. KAVANAGH, and P. D. PARKER. Search for Li^4 518
BATCHELOR, R. (see Gove, H. E.) 177
BAUM, J. L., D. F. BREWER, J. G. DAUNT, and D. O. EDWARDS. Measurements of the melting curve of pure He^3 below the minimum 127
BEARD, D. B. High nuclear excitation as a nuclear force probe 432
BELL, J. S. and E. J. SQUIRES. A formal optical model 96
BERMAN, S. M. (see Gell-Mann, Murray) 99
BERNARDES, NEWTON and HENRY PRIMAKOFF. Theory of solid He^3 144(E)
BIRDSALL, C. K. and ALLAN J. LICHTENBERG. Traveling wave focusing for plasma containment 163
BLAIR, I. M. (see Astbury, A.) 476
BLEWITT, T. H., R. R. COLTMAN, and C. E. KLABUNDE. Stored energy of irradiated copper 132
BLOCK, M. M., E. B. BRUCKER, I. S. HUGHES, T. KIKUCHI, C. MELTZER, F. ANDERSON, A. PEVSNER, E. M. HARTH, JACK LEITNER, and H. O. COHN. Observation of He^4 hyperfragments from K^--He interactions; the $K^- - \Lambda$ relative parity 291
BLOOM, S. D., N. K. GLENDENNING, and S. A. MOSZKOWSKI. Proton-neutron interaction and the (p, n) reaction in mirror nuclei 98
BOLLINGER, L. M., R. E. COTÉ, and T. J. KENNETT. Fluctuations in partial radiation widths 376
BOLSTERLI, M. (see Brown, G. E.) 472
BÖMMEL, H. and K. DRANSFELD. Excitation of hypersonic waves by ferromagnetic resonance 83
BOUCHIAT, CLAUDE C. Theory of the vector interaction with a conserved current and the beta decay of Na^{24}-Al^{24} nuclei 516
BOYLE, W. S. (see Weinreich, G.) 244(E)
BOYNE, H. S. (see Franken, P. A.) 67(E)
BRAILSFORD, A. D. and A. W. OVERHAUSER. Theory of the resistance minimum in dilute paramagnetic alloys 331
BREWER, D. F. (see Baum, J. L.) 127

BRISSON, J. C., J. DETOEF, P. FALK-VAIRANT, L. VAN ROSSUM, G. VALLADAS, and LUKE C. L. YUAN. Measurements on the $\pi^{\pm}$-p total scattering cross sections in the energy range of 0.4 to 1.5 Bev 561
BROCKHOUSE, B. N. and N. K. POPE. Time-dependent pair correlations in liquid lead 259
BROSSEL, J., S. GESCHWIND, and A. L. SCHAWLOW. Optical detection of paramagnetic resonance in crystals at low temperatures 548
BROWN, G. E. and M. BOLSTERLI. Dipole state in nuclei 472
——— (see Mayers, D. F.) 90
BROWN, J. L., H. C. BRYANT, R. A. BURNSTEIN, R. W. HARTUNG, D. A. GLASER, J. A. KADYK, D. SINCLAIR, G. H. TRILLING, J. C. VANDER VELDE, and J. D. VAN PUTTEN. Direct proof of θ_1^0 neutral decay 51
———, H. C. BRYANT, R. A. BURNSTEIN, D. A. GLASER, R. W. HARTUNG, J. A. KADYK, D. SINCLAIR, G. H. TRILLING, J. C. VANDER VELDE, and J. D. VAN PUTTEN. Neutral branching ratios of Λ and K^0 particles 563
BROWN, R. R. and R. G. D'ARCY. Observations of solar flare radiation at high latitude during the period July 10-17, 1959 390
BRUCKER, E. B. (see Block, M. M.) 291
BRUNER, L. J. Internal friction in iron at low temperatures 411
BRYANT, H. C. (see Brown, J. L.) 51
——— (see Brown, J. L.) 563
BURNSTEIN, R. A. (see Brown, J. L.) 51
——— (see Brown, J. L.) 563

CAPLAN, P. J. (see Theissing, H. H.) 460
CARIS, JOHN C. (see Perkins, Walton A.) 56
CARMICHAEL, H. and J. F. STELJES. Unusual cosmic-ray fluctuations on July 17 and 18, 1959 392
CARVER, J. H. and G. A. JONES. Distribution of partial radiative widths in Cu^{59} following proton capture in Ni^{58} 559
——— and G. A. JONES. Distribution of total radiation widths of Cu^{59} 276
CHADAN, K. and S. ONEDA. Leptonic decay modes of the K meson 292
CHAMBERLAIN, O. (see Elioff, T.) 285
CHERRY, A. R. (see Cummerow, R. L.) 367; 441(E)
CHICK, BRUCE B. (see Dobbs, Roland E.) 332
CHOW, L. Y. (see White, J. A.) 428
CLASS, C. M., R. H. DAVIS, and J. H. JOHNSON. Evidence for shell-model states in Sc^{41} 41
CLOGSTON, A. M. (see Schawlow, A. L.) 271
——— (see Spencer, E. G.) 32
COCHRAN, W. Crystal stability and the theory of ferroelectricity 412
COHEN, S. G., P. S. FISHER, and E. K. WARBURTON. Capture gamma rays from O^{15} and O^{16} in the region of the giant resonance 433
COHEN, M. H. (see Känzig, W.) 509
COHN, H. O. (see Block, M. M.) 291
COLEGROVE, F. D., P. A. FRANKEN, R. R. LEWIS, and R. H. SANDS. Novel method of spectroscopy with applications to precision fine structure measurements 420
COLLINS, R. J. (see Geschwind, S.) 545
COLTMAN, R. R. (see Blewitt, T. H.) 132
CONNOR, DONALD. Measurement of the nuclear g factor of Li^8 429
COOPER, LEON N. Specific heat measurements and the energy gap in superconductors 17
CORLISS, L. M., J. M. HASTINGS, and R. J. WEISS. Antiphase antiferromagnetic structure of chromium 211
COTÉ, R. E. (see Bollinger, L. M.) 376
COWEN, J. A., W. R. SCHAFER, and R. D. SPENCE. Polarization of the Al^{27} nuclei in ruby 13
COX, B. (see Adam, J.) 543
CRAWFORD, FRANK S., JR., ROGER L. DOUGLASS, MYRON L. GOOD, GEORGE R. KALBFLEISCH, M. LYNN STEVENSON, and HAROLD K. TICHO. Charge independence in hyperon production 394
CRAWFORD, J. A. Fermi acceleration of electrons in the outer Van Allen belt 316
CROWE, KENNETH M. (see Haddock, Roy P.) 478
CRUT, M. and N. S. WALL. Measurement of the spin and parity of the anomalous inelastic states in Ni^{58} and Ni^{60} 520
CUMMEROW, R. L. and A. R. CHERRY. Dislocation pinning in n-type germanium 367; 441(E)
CZIRR, JOHN B. (see Haddock, Roy P.) 478

D'ARCY, R. G. (see Brown, R. R.) 390
DAS GUPTA, K. Smekal-Raman type modified x-ray scattering 38
DAUNT, J. G. (see Baum, J. L.) 127
DAVIS, R. H. (see Class, C. M.) 41
DAY, THOMAS B., G. A. SNOW, and J. SUCHER. Suppression of P-state capture in (K^-, p) atoms 61
de GENNES, P.-G. Canted spin arrangements 209
DETOEF, J. (see Brisson, J. C.) 561
DIAMOND, R. M. (see Stephens, F. S., Jr.) 435; 572(E)
DIAZ, JUSTO, SELIG N. KAPLAN, BURNS MacDONALD, and ROBERT V. PYLE. Fission of U^{238} induced by μ^- capture 234
DIBBLE, WILLIAM E. Many-particle cooperative scattering of x-rays in the two-crystal spectrometer 131
DIETER, F. A. (see Theissing, H. H.) 460
DILLON, J. F., JR. and J. W. NIELSEN. Effects of rare earth impurities on ferrimagnetic resonance in yttrium iron garnet 30
DIMMOCK, J. O. (see Wheeler, R. G.) 372
DOBBIE, C. B. (see Kolb, Alan C.) 5
DOBBS, ROLAND E., BRUCE B. CHICK, and ROHN TRUELL. Attenuation of sound in a germanium crystal at ultra-high frequencies and low temperatures 332
DONAHUE, T. M. and F. HUSHFAR. Formation of negative ions in CO by electron capture from fast hydrogen atoms 470
DONNELLY, R. J. Experiments on the hydrodynamic stability of helium II between rotating cylinders 507
DOUGLASS, ROGER L. (see Crawford, Frank S., Jr.) 394
DRAKE, C. (see White, J. A.) 428
DRANSFELD, K. (see Bömmel, H.) 83
DUNCAN, M. M. (see Newson, Henry W.) 45

EDMONDS, D. (see Arp, V.) 212
EDWARDS, D. O. (see Baum, J. L.) 127
EHRENREICH, H. (see Holonyak, N., Jr.) 167
EHRENSTEIN, G., C. H. TOWNES, and M. J. STEVENSON. Ground state Λ-doubling transitions of OH radical 40
EKSPONG, A. G., Å. FRISK, and B. E. RONNE. $_{\Lambda}H^4$ hyperfragment emitted from an antiproton capture star 103
ELIOFF, T., L. AGNEW, O. CHAMBERLAIN, H. STEINER, C. WIEGAND, and T. YPSILANTIS. $\bar{p}$-p cross sections from 534 to 1068 Mev 285
ELY, R. P. and D. H. FRISCH. Search for $\pi_{10}^0 \to 3\gamma$ 565
——— (see Hyman, L. G.) 93
ERICKSON, W. C. Radio emission in the outer corona 365

FALK-VAIRANT, P. (see Brisson, J. C.) 561
FAWCETT, E. Cyclotron resonance in aluminum 139
FEHER, GEORGE. Nuclear polarization via "hot" conduction electrons 135
———, D. K. WILSON, and E. A. GERE. Electron spin resonance experiments on shallow donors in germanium 25
FEINBERG, G., P. KABIR, and S. WEINBERG. Transformation of muons into electrons 527
——— (see Weinberg, S.) 111; 244(E)
FELDMAN, GORDON and T. FULTON. S-matrix poles in the determination of parities 64
FERRELL, RICHARD A. Knight shift in superconductors 262
FISCHER, J., B. LEONTIC, A. LUNDBY, R. MEUNIER, and J. P. STROOT. Measurement of μ^+ lifetime 349
FISHER, P. S. (see Cohen, S. G.) 433
FOLDY, LESLIE L. Electric polarizability of the neutron 105
FONER, S., L. R. MOMO, and A. MAYER. Multilevel pulsed-field maser for generation of high frequencies 36
FOWLER, WILLIAM B. (see Goldhaber, Gerson) 181
FRANKEN, P. A. and H. S. BOYNE. Effect of nuclear electric dipole moments on nuclear spin relaxation 67(E)
——— (see Colegrove, F. D.) 420
FREDEN, STANLEY C. and R. STEPHEN WHITE. Protons in the earth's magnetic field 9; 145(E)
FREIER, P. S. (see Ney, E. P.) 183
FRERICHS, R. and I. LIBERMAN. Electroluminescence at point contacts in cuprous oxide and the mobility of Cu^+ ions at room temperature 214
FRISCH, D. H. (see Ely, R. P.) 565
——— (see Hyman, L. G.) 93
FRISCH, O. R. and D. N. OLSON. Detection of coherent bremsstrahlung from crystals 141

FRISK, Å. (see Ekspong, A. G.) 103
FRONSDAL, C. and S. L. GLASHOW. μ-meson decay 570
FULTON, T. (see Feldman, Gordon) 64

GARDNER, C. G. and T. A. WELTON. Possibility of studying the Λ-hyperon–nucleon force by low-energy scattering 281
GAVENDA, J. D. (see Morse, R. W.) 15; 193(E)
GELBERG, ADRIAN. Electron capture decay of oriented nuclei 378
GELL-MANN, MURRAY and S. M. BERMAN. Electromagnetic corrections to the B^{12} - N^{12} β-spectrum ratio 99
GENEUX, EDMOND and BARBARA WANDERS-VINCENZ. Magnetic dipole resonance of excited levels in free ions of Cd II and Zn II 422
GERE, E. A. (see Feher, George) 25
GESCHWIND, S. Sign of the ground-state cubic crystal field splitting parameter in Fe^{3+} 207
———, R. J. COLLINS, and A. L. SCHAWLOW. Optical detection of paramagnetic resonance in an excited state of Cr^{3+} in Al_2O_3 545
——— (see Brossel, J.) 548
GINSBERG, D. M., P. L. RICHARDS, and M. TINKHAM. Apparent structure on the far infrared energy gap in superconducting lead and mercury 337
GLASER, D. A. (see Brown, J. L.) 51
——— (see Brown, J. L.) 563
GLASHOW, S. L. (see Fronsdal, C.) 570
GLENDENNING, N. K. (see Bloom, S. D.) 98
GOLDBERG, EDWARD D. (see Lal, Devendra) 380
GOLDHABER, GERSON, WILLIAM B. FOWLER, SULAMITH GOLDHABER, T. F. HOANG, THEODORE E. KALOGEROPOULOS, and WILSON M. POWELL. Pion-pion correlations in antiproton annihilation events 181
GOLDHABER, SULAMITH (see Goldhaber, Gerson) 181
GOOD, MYRON L. (see Crawford, Frank S., Jr.) 394
GOODWIN, LESTER K., ROBERT W. KENNEY, and VICTOR PEREZ-MENDEZ. Experimental evidence for D waves in $\pi^- - p$ scattering at 370 and 427 Mev 522
GOSSARD, A. C. and A. M. PORTIS. Observation of nuclear resonance in a ferromagnet 164
GOVE, H. E., A. E. LITHERLAND, and R. BATCHELOR. Proton capture gamma rays in the giant resonance region 177
GREEN, J. J. (see Schlömann, E.) 129
GRIEM, H. R. (see Kolb, Alan C.) 5
GRIFFIN, J. J. and M. RICH. Moments of inertia of even-even rare earths 342
GUERON, M. and CH. RYTER. Overhauser effect in metallic lithium 338

HADDOCK, ROY P., ALEXANDER ABASHIAN, KENNETH M. CROWE, and JOHN B. CZIRR. Pion mass measurements using neutron time-of-flight techniques 478
HALL, R. N. (see Holonyak, N., Jr.) 167
HARTH, E. M. (see Block, M. M.) 291
HARTING, D., J. C. KLUYVER, A. KUSUMEGI, R. RIGOPOULOS, A. M. SACHS, G. TIBELL, G. VANDERHAEGHE, and G. WEBER. Experiment on charge independence in pion interactions 52
HARTUNG, R. W. (see Brown, J. L.) 51
——— (see Brown, J. L.) 563
HASTINGS, J. M. (see Corliss, L. M.) 211
HELLAND, JEROME A. (see Longo, Michael J.) 568
HESS, WILMOT N. Van Allen belt protons from cosmic-ray neutron leakage 11; 145(E)
——— (see Longo, Michael J.) 568
HEWITT, R. R. and W. D. KNIGHT. Nuclear quadrupole resonance in metallic indium 18
HIGGS, P. W. Integration of secondary constraints in quantized general relativity 66(E)
HOANG, T. F. (see Goldhaber, Gerson) 181
HOLONYAK, N., JR., I. A. LESK, R. N. HALL, J. J. TIEMANN, and H. EHRENREICH. Direct observation of phonons during tunneling in narrow junction diodes 167
HOLSTEIN, T. (see Kjeldaas, T., Jr.) 299(E)
HOSKINS, R. H. Spin-level inversion and spin-temperature mixing in ruby 174
HUBBARD, J. Calculation of partition functions 77
HUGHES, D. J., H. PALEVSKY, W. KLEY, and E. TUNKELO. Atomic motions in water by scattering of cold neutrons 91
HUGHES, I. S. (see Block, M. M.) 291
HUGHES, V. W. (see White, J. A.) 428
HUSHFAR, F. (see Donahue, T. M.) 470

HUSSAIN, M. (see Astbury, A.) 476
HYMAN, L. G., R. ELY, D. H. FRISCH, and M. A. WAHLIG. Scattering of 50- to 140-Mev photons by protons and deuterons 93

JACOBSEN, E. H., N. S. SHIREN, and E. B. TUCKER. Effects of 9.2-kMc/sec ultrasonics on electron spin resonances in quartz 81
JARMIE, NELSON and MYRON G. SILBERT. Oxygen-20 50
JAVAN, A. Possibility of production of negative temperature in gas discharges 87
JOHNSON, J. H. (see Class, C. M.) 41
JOHNSON, KENNETH and BRUNO ZUMINO. Gauge dependence of the wave-function renormalization constant in quantum electrodynamics 351
JONES, G. A. (see Carver, J. H.) 276
——— (see Carver, J. H.) 559

KABIR, P. (see Feinberg G.) 527
KADANOFF, LEO P. (see Martin, Paul C.) 322
KADYK, J. A. (see Brown, J. L.) 51
——— (see Brown, J. L.) 563
KAISER, W. and G. H. WHEATLEY. Hot electrons and carrier multiplication in silicon at low temperature 334
KALBFLEISCH, GEORGE R. (see Crawford, Frank S., Jr.) 394
KALOGEROPOULOS, THEODORE E. (see Goldhaber, Gerson) 181
KANE, EVAN O. (see Morgan, John V.) 466
KÄNZIG, W. and M. H. COHEN. Paramagnetic resonance of oxygen in alkali halides 509
KAPLAN, SELIG N. (see Diaz, Justo) 234
KAPLON, M. F. (see Yamanouchi, T.) 283
KAUFMANN, RICHARD and RICHARD WOLFGANG. Complex nucleon transfer reactions of heavy ions 232
KAUS, PETER. Role of negative effective mass in negative resistance 20
KAVANAGH, R. W. (see Bashkin, S.) 518
KEMP, M. A. R. (see Astbury, A.) 476
KENNETT, T. J. (see Bollinger, L. M.) 376
KENNEY, ROBERT W. (see Goodwin, Lester K.) 522
——— (see Perkins, Walton A.) 56
KENT, R. L. (see Badessa, R. S.) 79
KERNAN, W. (see York, C. M.) 288
KIKUCHI, C. (see Lambe, J.) 270
KIKUCHI, T. (see Block, M. M.) 291
KIM, C. O. (see York, C. M.) 288
KITTEL, C. Mechanism for anomalous magnetocrystalline anisotropy peaks in ferromagnetic crystals 169
KJELDAAS, T., JR. and T. HOLSTEIN. Oscillatory magneto-acoustic effect in metals 299(E)
KLABUNDE, C. E. (see Blewitt, T. H.) 132
KLEIN, A. (see Tzoar, N.) 145(E)
KLEY, W. (see Hughes, D. J.) 91
KLUYVER, J. C. (see Harting, D.) 52
KNAPP, EDWARD A. (see Perkins, Walton A.) 56
KNIGHT, W. D. (see Hewitt, R. R.) 18
KNOX, W. J. (see Anderson, C. E.) 557
KOIDE, MINORU (see Lal, Devendra) 380
KOLB, ALAN C., C. B. DOBBIE, and H. R. GRIEM. Field mixing and associated neutron production in a plasma 5
KOMAI, L. G. (see Tamura, T.) 344
KOMURA, Y., Y. TOMIIE, and R. NATHANS. Scattering factor for outer electrons in ordered Fe_3Al 268
KORRINGA, JAN (see Torrey, H. C.) 418
KRALL, N. A. and E. GERJUOY. De-excitation of μ-mesonic atoms 142
KUHLMANN-WILSDORF, D. (see Wilsdorf, H. G. F.) 170
KURATH, DIETER. Magnetic moment calculation for Li^8 431
KUSUMEGI, A. (see Harting, D.) 52

LAL, DEVENDRA, EDWARD D. GOLDBERG, and MINORU KOIDE. Cosmic-ray-produced Si^{32} in nature 380
LAMB, J., M. REDWOOD, and Z. SHTEINSHLEIFER. Absorption of compressional waves in solids from 100 to 1000 Mc/sec 28
LAMBE, J., J. BAKER, and C. KIKUCHI. Photosensitive spin resonance in CdS 270
LANDER, RICHARD L., WILSON M. POWELL, and HOWARD S. WHITE. Parity conservation in hyperon production by 1.15-Bev/c K^- mesons on propane 236
LANDOVITZ, LEON F. and L. MARSHALL. Parity of the second pion resonance 190
——— and L. MARSHALL. Proton polarization in multiple pion production as a consequence of the isobar model 106
LANGENBERG, D. N. and T. W. MOORE. Cyclotron resonance in aluminum 137

——— and T. W. MOORE. Cyclotron resonance in copper 328

LAPONSKY, A. B. and N. REY WHETTEN. Dependence of secondary electron emission on crystal orientation 510

LAX, BENJAMIN (see Roth, Laura M.) 217

LeCRAW, R. C. (see Spencer, E. G.) 32

LEE, JULIET and N. P. SAMIOS. Search for rare decay modes of the μ^+ meson 55

LEITNER, JACK, PAUL NORDIN, JR., ARTHUR H. ROSENFELD, FRANK T. SOLMITZ, and ROBERT D. TRIPP. Search for leptonic decays of the Σ 186

———, PAUL NORDIN, JR., ARTHUR H. ROSENFELD, FRANK T. SOLMITZ, and ROBERT D. TRIPP. Σ spin and parity conservation in $K^- + p \rightarrow \Sigma^+ + \pi^-$ 238

——— (see Block, M. M.) 291

LELAND, W. (see Nagle, D. E.) 318

LEONTIC, B. (see Fischer, J.) 349

LESK, I. A. (see Holonyak, N., Jr.) 167

LEWIS, R. R. (see Colegrove, F. D.) 420

LIBERMAN, I. (see Frerichs, R.) 214

LICHTENBERG, ALLAN J. (see Birdsall, C. K.) 163

LITHERLAND, A. E. (see Gove, H. E.) 177

LOEBNER, E. E. and E. W. POOR, JR. Bimolecular electroluminescent transitions in GaP 23

LOKANATHAN, S. (see Wilkinson, D. H.) 397

LONGO, MICHAEL J., JEROME A. HELLAND, WILMOT N. HESS, BURTON J. MOYER, and VICTOR PEREZ-MENDEZ. High-energy total cross sections for positive pions and protons on hydrogen 568

LUCKEY, P. D., L. S. OSBORNE, and J. J. RUSSELL. Photoproduction of neutral mesons from hydrogen near threshold 240

LUNDBY, A. (see Fischer, J.) 349

MacDONALD, BURNS (see Diaz, Justo) 234

MARSHALL, L. (see Landovitz, Leon F.) 106

——— (see Landovitz, Leon F.) 190

MARSHALL, W. (see Schiffer, J. P.) 556

MARTIN, PAUL C. and LEO P. KADANOFF. Knight shift in superconductors 322

MATTHEWS, P. T. and J. L. URETSKY. $K^+ - K^0$ mass difference 297

MATTHIAS, B. T. (see Suhl, H.) 552

MATTIS, D. C. and M. J. STEVENSON. Theory of negative-mass cyclotron resonance 18

MATTUCK, R. D. and M. W. P. STRANDBERG. Quadrupole selection rule in iron group spin-phonon interactions 369

——— and M. W. P. STRANDBERG. Saturation of paramagnetic spins by 13-Mc/sec ultrasonic phonons 550

MAYER, A. (see Foner, S.) 36

MAYERS, D. F., G. E. BROWN, and E. A. SANDERSON. Lamb shift and energy level of a tightly bound electron 90

McKEOWN, MICHAEL (see Scharff-Goldhaber) 47

MELTZER, C. (see Block, M. M.) 291

MEUNIER, R. (see Fischer, J.) 349

MILLS, R. L., A. M. SESSLER, S. A. MOSZKOWSKI, and D. G. SHANKLAND. Superfluidity of nuclear matter 381

MILONE, CARMELO. Energy spectrum of photoneutrons from oxygen 43

MOMO, L. R. (see Foner, S.) 36

MOORE, T. W. (see Langenberg, D. N.) 137

——— (see Langenberg, D. N.) 328

MORGAN, JOHN V. and EVAN O. KANE. Observation of direct tunneling in germanium 466

MORIN, F. J. Oxides which show a metal-to-insulator transition at the Néel temperature 34

MORSE, R. W., T. OLSEN, and J. D. GAVENDA. Evidence for anisotropy of the superconducting energy gap from ultrasonic attenuation 15; 193(E)

MOSZKOWSKI, S. A. (see Bloom, S. D.) 98

——— (see Mills, R. L.) 381

MOYER, BURTON J. (see Longo, Michael J.) 568

MUIRHEAD, H. (see Astbury, A.) 476

NAGLE, D. E., W. E. QUINN, W. B. RIESENFELD, and W. LELAND. Ion temperature in Scylla, as determined from the reaction D(d, p)T 318

NATHANS, R. (see Komura, Y.) 268

NEIGHBOURS, J. R. and G. A. ALERS. Magnetic effects on shear wave attenuation in single crystal copper 265

NEWSON, HENRY W. and M. M. DUNCAN. Shell effects at high excitation energies 45

NEY, E. P., J. R. WINCKLER, and P. S. FREIER. Protons from the sun on May 12, 1959 183

NIELSEN, J. W. (see Dillon, J. F., Jr.) 30
NORDIN, PAUL, JR. (see Leitner, Jack) 186
——— (see Leitner, Jack) 238
NOWELL, J. C. (see Badessa, R. S.) 79
NOYES, H. PIERRE and DAVID Y. WONG. Modification of the effective-range formula for nucleon-nucleon scattering 191

OFER, S. and A. SCHWARZSCHILD. Nuclear resonance fluorescence with solid sources: Mg^{24}, Si^{28}, Cr^{52}, Sr^{88}, and Ce^{140} 384
OLSEN, T. (see Morse, R. W.) 15; 193(E)
OLSON, D. N. (see Frisch, O. R.) 141
ONEDA, S. (see Chadan, K.) 292
OSBORNE, L. S. (see Luckey, P. D.) 240
OVERHAUSER, A. W. New mechanism of antiferromagnetism 414
——— (see Brailsford, A. D.) 331

PACK, J. L. (see Phelps, A. V.) 340
PAIS, A. Notes on antibaryon interactions 242
PAKE, G. E. and T. R. TUTTLE, JR. Anomalous loss of resolution of paramagnetic resonance hyperfine structure in liquids 423
PALEVSKY, H. (see Hughes, D. J.) 91
PARKER, P. D. (see Bashkin, S.) 518
PERES, ASHER. Some gravitational waves 571
PEREZ-MENDEZ, VICTOR (see Goodwin, Lester K.) 522
——— (see Longo, Michael J.) 568
——— (see Perkins, Walton A.) 56
PERKINS, WALTON A., JOHN C. CARIS, ROBERT W. KENNEY, EDWARD A. KNAPP, and VICTOR PEREZ-MENDEZ. Pion production by pions 56
PERLMAN, I. (see Stephens, F. S., Jr.) 435; 572(E)
PETERSEN, R. (see Arp, V.) 212
PEVSNER, A. (see Block, M. M.) 291
PHELPS, A. V. and J. L. PACK. Electron collision frequencies in nitrogen and in the lower ionosphere 340
PHILLIPS, J. C. Cyclotron resonance in metals 327
PHILLIPS, R. J. N. Prediction of deuteron polarization from d - α scattering 101
PLANO, R., A. PRODELL, N. SAMIOS, M. SCHWARTZ, and J. STEINBERGER. Parity of the neutral pion 525
POOR, E. W., JR. (see Loebner, E. E.) 23
POPE, N. K. (see Brockhouse, B. N.) 259
PORTIS, A. M. (see Gossard, A. C.) 164
POUND, R. V. and G. A. REBKA, JR. Gravitational red-shift in nuclear resonance 439
——— and G. A. REBKA, JR. Resonant absorption of the 14.4-kev γ ray from 0.10-μsec Fe^{57} 554
POWELL, WILSON M. (see Goldhaber, Gerson) 181
——— (see Lander, Richard L.) 236
PRIMAKOFF, HENRY (see Bernardes, Newton) 144(E)
PRODELL, A. (see Plano, R.) 525
PRYCE, M. H. L. Sign of g in magnetic resonance, and the sign of the quadrupole moment of Np^{237} 375
PYLE, ROBERT V. (see Diaz, Justo) 234

QUINN, W. E. (see Nagle, D. E.) 318
QUINTON, A. R. (see Anderson, C. E.) 557

RABBINER, N. (see Theissing, H. H.) 460
RAPHAEL, R. (see Tzoar, N.) 145(E)
RAYNE, J. A. Temperature dependence of the absorptivity of copper in the near infrared 512
REBKA, G. A., JR. (see Pound, R. V.) 439
——— (see Pound, R. V.) 554
REDFIELD, ALFRED G. Nuclear spin relaxation time in superconducting aluminum 85
REDWOOD, M. (see Lamb, J.) 28
REIFFEL, L. Pressure effects and configuration coordinate models of KCl(Tl) 215
REYNOLDS, DONALD C. (see Warschauer, Douglas M.) 370
RICH, M. (see Griffin, J. J.) 342
RICHARDS, P. L. (see Ginsberg, D. M.) 337
RIESENFELD, W. B. (see Nagle, D. E.) 318
RIGOPOULOS, R. (see Harting, D.) 52
ROBINSON, D. K. (see Wilkinson, D. H.) 397
RODBERG, LEONARD S. Pion production and the pion-pion interaction 58
RODGERS, K. F. (see Weinreich, G.) 244(E)
RONNE, B. E. (see Ekspong, A. G.) 103
ROSE, M. E. Method for producing aligned deuterons 387
ROSENFELD, ARTHUR H. (see Leitner, Jack) 186
——— (see Leitner, Jack) 238
ROSS, MARC (see Wong, Wen-Nong) 398
ROTH, LAURA M. and BENJAMIN LAX.

g factor of electrons in germanium 217
RUBBIA, C. (see Baker, W. F.) 179
RUSSELL, J. J. (see Luckey, P. D.) 240
RYTER, CH. (see Gueron, M.) 338

SACHS, A. M. (see Harting, D.) 52
SAMIOS, N. P. (see Lee, Juliet) 55
——— (see Plano, R.) 525
SANDERS, J. H. Optical maser design 86
SANDERSON, E. A. (see Mayers, D. F.) 90
SANDS, R. H. (see Colegrove, F. D.) 420
SCHAFER, W. R. (see Cowen, J. A.) 13
SCHARFF-GOLDHABER, GERTRUDE and MICHAEL McKEOWN. Triple isomerism in Ir^{192} 47
SCHAWLOW, A. L., D. L. WOOD, and A. M. CLOGSTON. Electronic spectra of exchange-coupled ion pairs in crystals 271
——— (see Brossel, J.) 548
——— (see Geschwind, S.) 545
——— (see Varsanyi, F.) 544
SCHIFFER, J. P. and W. MARSHALL. Recoilless resonance absorption of gamma rays in Fe^{57} 556
SCHLÖMANN, E. and J. J. GREEN. Fine structure in the decline of the ferromagnetic resonance absorption with increasing power level 129
SCHRIEFFER, J. R. Knight shift in superconductors 323
SCHWARTZ, M. (see Plano, R.) 525
SCHWARZSCHILD, A. (see Ofer, S.) 384
SCHWINGER, JULIAN. Field theory commutators 296
SEEVERS, D. O. (see Torrey, H. C.) 418
SEGEL, S. L. (see Barnes, R. G.) 462
SEKULA, S. T. Resistance minimum and resistivity of copper at low temperatures 416
SELLSCHOP, J. P. F. Angular distributions from stripping reactions of low *Q* values 346
SESSLER, A. M. (see Mills, R. L.) 381
SHANKLAND, D. G. (see Mills, R. L.) 381
SHARP, DAVID. Variational principle for geometrodynamics 108
SHERRILL, F. A. (see Wittels, M. C.) 176
SHIREN, N. S. (see Jacobsen, E. H.) 81
SHTEINSHLEIFER, Z. (see Lamb, J.) 28
SILBERT, G. (see Jarmie, Nelson) 50
SINCLAIR, D. (see Brown, J. L.) 51
——— (see Brown, J. L.) 563
SINGER, S. F. Cause of the minimum in the earth's radiation belt 188
SIRLIN, ALBERTO and R. SPITZER. Possible methods for the determination of strange-particle parities 110
SNOW, G. A. (see Day, Thomas B.) 61
SOLMITZ, FRANK T. (see Leitner, Jack) 186
——— (see Leitner, Jack) 238
SPENCE, R. D. (see Cowen, J. A.) 13
SPENCER, E. G., R. C. LeCRAW, and A. M. CLOGSTON. Low-temperature line-width maximum in yttrium iron garnet 32
SPITZER, R. (see Sirlin, Alberto) 110
SQUIRES, E. J. (see Bell, J. S.) 96
STEFFEN, R. M. Search for higher-order effects in allowed beta decay 277
STEINBERGER, J. (see Plano, R.) 525
STEINER, H. (see Elioff, T.) 285
STELJES, J. F. (see Carmichael, H.) 392
STEPHENS, F. S., JR., R. M. DIAMOND, and I. PERLMAN. Multiple Coulomb excitation in Th^{232} and U^{238} 435; 572(E)
STEVENSON, M. J. Cyclotron resonance in $CdAs_2$ 464
——— (see Ehrenstein, G.) 40
——— (see Mattis, D. C.) 18
STEVENSON, M. LYNN (see Crawford, Frank S., Jr.) 394
ST. LORANT, S. J. (see Wilkinson, D. H.) 397
STRANDBERG, M. W. P. (see Mattuck, R. D.) 369
——— (see Mattuck, R. D.) 550
STROOT, J. P. (see Fischer, J.) 349
SUCHER, J. (see Day, Thomas B.) 61
SUHL, H., B. T. MATTHIAS, and L. R. WALKER. Bardeen-Cooper-Schrieffer theory of superconductivity in the case of overlapping bands 552
SWEETMAN, D. R. Dissociation of H_2^+ ions by hydrogen 425

TAMURA, T. and L. G. KOMAI. New model for vibrational spectra in even-even nuclei 344
TELEGDI, V. L. Consequences of atomic conversion for the interpretation of experiments on the spin-dependence of muon absorption 59
THEISSING, H. H., P. J. CAPLAN, F. A. DIETER, and N. RABBINER. Optical pumping in crystals 460

TIBELL, G. (see Harting, D.) 52
TICHO, HAROLD K. (see Crawford, Frank S., Jr.) 394
TIEMANN, J. J. (see Holonyak, N., Jr.) 167
TINKHAM, M. (see Ginsberg, D. M.) 337
TITLE, R. S. Paramagnetic resonance detection of the optical excitation of an infrared stimulable phosphor 273
TOMIIE, Y. (see Komura, Y.) 268
TORREY, H. C., JAN KORRINGA, D. O. SEEVERS, and JEAN UEBERSFELD. Magnetic spin pumping in fluids contained in porous media 418
TOWNES, C. H. (see Ehrenstein, G.) 40
TRILLING, G. H. (see Brown, J. L.) 51
——— (see Brown, J. L.) 563
TRIPP, ROBERT D. (see Leitner, Jack) 186
——— (see Leitner, Jack) 238
TRUELL, ROHN (see Dobbs, Roland E.) 332
TUCK, JAMES L. Plasma jet piercing of magnetic fields and entropy trapping into a conservative system 313
TUCKER, E. B. (see Jacobsen, E. H.) 81
TUNKELO, E. (see Hughes, D. J.) 91
TUTTLE, T. R., JR. (see Pake, G. E.) 423
TZOAR, N., R. RAPHAEL, and A. KLEIN. Meson-theoretical origin of the spin-orbit coupling between two nucleons 145(E)

UEBERSFELD, JEAN (see Torrey, H. C.) 418
ULMER, KURT. New method for the evaluation of h/e from the quantum limit of the continuous x-ray spectrum 514
URETSKY, J. L. (see Matthews, P. T.) 297

VALLADAS, G. (see Brisson, J. C.) 561
VANDERHAEGHE, G. (see Harting, D.) 52
VANDER VELDE, J. C. (see Brown, J. L.) 51
——— (see Brown, J. L.) 563
VAN PUTTEN, J. C. (see Brown, J. L.) 51
——— (see Brown, J. L.) 563
VAN ROSSUM, L. (see Brisson, J. C.) 561
VARSANYI, F., D. L. WOOD, and A. L. SCHAWLOW. Self-absorption and trapping of sharp-line resonance radiation in ruby 544
VINTI, JOHN P. New approach in the theory of satellite orbits 8
VOSS, R. G. P. (see Astbury, A.) 476

WAHLIG, M. A. (see Hyman, L. G.) 93
WALKER, L. R. (see Suhl, H.) 552
WALL, N. S. (see Crut, M.) 520
WANDERS-VINCENZ, BARBARA (see Geneux, Edmond) 422
WARBURTON, E. K. (see Cohen, S. G.) 433
WARSCHAUER, DOUGLAS M. and DONALD C. REYNOLDS. Edge and impurity emission in cadmium sulfide 370
WEBER, G. (see Harting, D.) 52
WEINBERG, S. and G. FEINBERG. Electromagnetic transitions between μ meson and electron 111; 244(E)
——— (see Feinberg G.) 527
WEINREICH, G., W. S. BOYLE, H. G. WHITE, and K. F. RODGERS. Valley-orbit splitting of arsenic donor ground state in germanium 244(E)
WEISS, R. J. (see Corliss, L. M.) 211
WELTON, T. A. (see Gardner, C. G.) 281
WHEATLEY, G. H. (see Kaiser, W.) 334
WHEELER, R. G. and J. O. DIMMOCK. Zeeman splitting of exciton lines in CdS 372
WHETTEN, N. REY (see Laponsky, A. B.) 510
WHITE, H. G. (see Weinreich, G.) 244(E)
WHITE, HOWARD S. (see Lander, Richard L.) 236
WHITE, J. A., L. Y. CHOW, C. DRAKE, and V. W. HUGHES. Hyperfine structure of the metastable triplet state of helium three 428
WHITE, R. STEPHEN (see Freden, Stanley C.) 9; 145(E)
WIEDER, IRWIN. Optical detection of paramagnetic resonance saturation in ruby 468
WIEGAND, C. (see Elioff, T.) 285
WILKINSON, D. H. Configurational assignments of giant photonuclear resonances 388
———, S. J. ST. LORANT, D. K. ROBINSON, and S. LOKANATHAN. Double-hyperfragment event 397
WILSDORF, H. G. F. Nature of radiation damage in nickel 172
——— and D. KUHLMANN-WILSDORF. Considerations on the interaction between thermal vacancies and dislocations 170
WILSON, D. K. (see Feher, George) 25
WINCKLER, J. R. (see Ney, E. P.) 183
WITTELS, M. C. and F. A. SHERRILL. Fission fragment damage in zirconia 176
WOLFGANG, RICHARD (see Kaufmann, Richard) 232
WONG, DAVID Y. (see Noyes, H. Pierre) 191

WONG, WEN-NONG and MARC ROSS. Theory of the high-energy peaks in pion-nucleon cross sections 398
WOOD, D. L. (see Schawlow, A. L.) 271
——— (see Varsanyi, F.) 544
YAMANOUCHI, T. Strangeness 2 meson 480
——— and M. F. KAPLON. Possible evidence for a negative heavy meson 283
YILMAZ, HUSEYIN. Two maser experiments to test general relativity 320
YORK, C. M., C. O. KIM, and W. KERNAN. Search for the reaction $\mu^+ + e^- \rightarrow \gamma + \gamma$ 288
YPSILANTIS, T. (see Elioff, T.) 285
YUAN, LUKE C. L. (see Brisson, J. C.) 561
ZUMINO, BRUNO (see Johnson, Kenneth) 351